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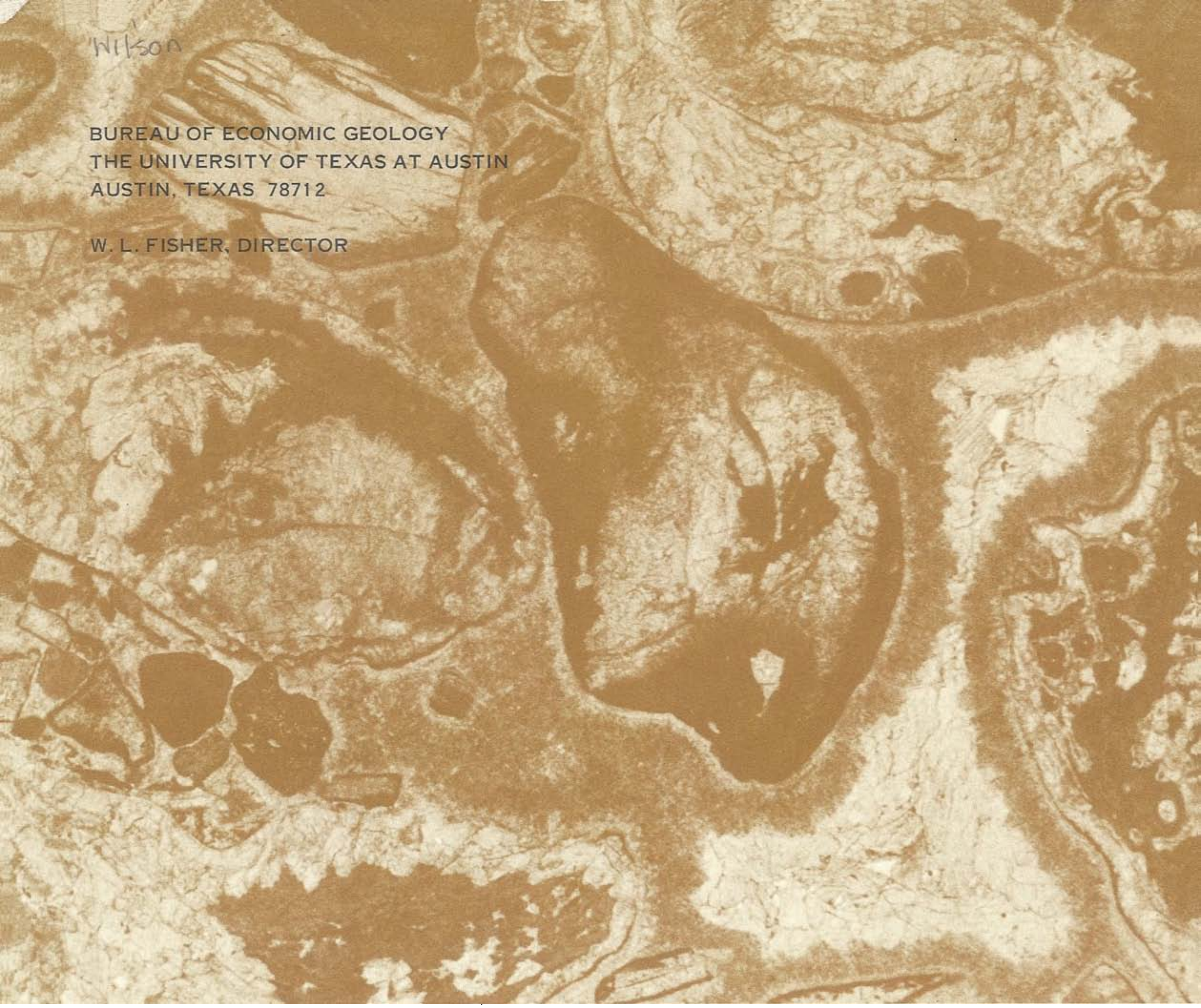

STUART CITY TREND LOWER CRETACEOUS, SOUTH TEXAS

A CARBONATE SHELF-MARGIN MODEL FOR HYDROCARBON EXPLORATION

BY D. G. BEBOUT AND R. G. LOUCKS

REPORT OF INVESTIGATIONS NO. 78
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A Carbonate Shelf-Margin Model for Hydrocarbon Exploration

D. G. Bebout and R. G. Loucks

SUMMARY

Lower Cretaceous shallow-water carbonates accumulated on a broad shelf which completely encircled the Gulf of Mexico. Biogenic growth climaxed along the basinward edge, or shelf margin, where a complex of reefs, banks, bars, and islands developed. The sediments reached a total thickness of 2,000 to 2,500 feet; numerous deep wells ranging in total depth from 11,000 to 20,000 feet have resulted in the discovery of a few marginally productive gas fields. The objectives of this study are: (1) to describe the depositional facies and environments present along this trend in order to provide a model for further hydrocarbon exploration along the Stuart City Trend and also in the deeper Sligo Trend, and (2) to identify diagenetic processes which relate to porosity distribution and might lead to the discovery of zones of higher porosity elsewhere along the trend.

The Stuart City carbonate rocks have been assigned to five major environments of deposition: shelf lagoon, shelf margin, upper shelf slope, lower shelf slope, and open marine. The shelf-lagoon facies include miliolid wackestone,[1] mollusk wackestone, toucasid wackestone, and mollusk-miliolid grainstone. These facies accumulated under generally low-energy conditions in water depths from 0 to 20 feet. In contrast, the narrow band of shelf-margin carbonates is made up of algae-encrusted miliolid-coral-caprinid packstone, coral-caprinid boundstone, requienid boundstone, and rudist grainstone, all of which accumulated in moderate- to high-energy waters and in less than 15 feet of water. Seaward of the shelf margin, the upper shelf-slope environment comprises the caprinid-coral wackestone and coral-stromatoporoid boundstone facies, and the lower shelf slope comprises the intraclast grainstone, echinoid packstone, and echinoid-mollusk wackestone facies. Further seaward, in water depths greater than 60 feet, the open-marine environment is represented by the planktonic foraminifer wackestone.

The most extensive diagenesis occurred in the grainstone bodies. Primary porosity within the grainstone facies of the shelf margin at the time of deposition is estimated to have been between 30 and 40 percent. Three types of diagenesis have occurred, several of which have aided in destruction of porosity—formation of micrite rims, cementation of grains (by isopachous, dripstone and meniscus, radiaxial, and equant cements), and neomorphism of shell material to equant calcite. The micrite rims and isopachous cement are of submarine origin and are synsedimentary. The dripstone and meniscus cement probably formed in the vadose zone, although some dripstone has been reported from intertidal beachrock. Physical evidence from this study suggests that the radiaxial cement formed very early in the shallow subsurface from phreatic-meteoric water. The last to be deposited was the equant cement, which in most grainstones completely plugs the little remaining porosity. This cement was precipitated after lithification and fracturing of the sediment but before stylolitization.

Several types of porosity have been recorded from cores of the Stuart City Trend: solution-enlarged interparticle, moldic, primary interparticle, primary intraparticle, and fracture. Primary intraparticle porosity, primary openings within the body chambers of organisms, is most widespread in its occurrence, but unless openings are connected by another type of porosity, permeability is low. The most effective porosity is primary interparticle which occurs between grains in grainstones and in primary vugs of boundstones. Primary porosity is preserved by rapid subsidence or early emplacement of hydrocarbons which prevent cementation by fresh water. Secondary solution-enlarged interparticle and moldic porosity

[1] The classification used here is from Dunham (1962). In accordance with the rules set up by Dunham, each carbonate rock name should be preceded by the word "lime" to distinguish it from dolomite or terrigenous sediments with the same texture. However, because of the lack of significant terrigenous sediments in this study, "lime" has been omitted from the names.

occur in the grainstone and boundstone facies but in lesser amounts; solution-enlarged porosity results from long periods of subaerial weathering.

Further exploration along the Stuart City Trend should concentrate on two different types of areas. Solution-enlarged porosity is found where the carbonate section was exposed for long periods of time; exposure most likely occurred where the trend crosses the low, positive San Marcos Arch, centering in DeWitt County. Primary interparticle porosity in the grainstone bodies can occur in areas in which subsidence rates were relatively high. Subsidence would remove the grainstones from the influence of phreatic-meteoric waters which tend to deposit thick, massive layers of cement in open pores.

INTRODUCTION

General Remarks

Lower Cretaceous shelf carbonates of Aptian, Albian, and Cenomanian age accumulated in a broad band which completely circled the Gulf of Mexico (fig. 1). These carbonates are well known on the outcrop in eastern Mexico and Central Texas and in the subsurface of the Yucatan Peninsula in eastern Mexico, South and East Texas, Central and South Louisiana, South Florida, and the Bahamas. Knowledge of these rocks in the subsurface is the result of exploration for oil in Lower Cretaceous carbonates throughout this area. Incentive for this oil exploration must be credited to the development of enormous oil fields discovered along the Golden Lane and the Poza Rica Trend on the Gulf Coast of central Mexico during the past 30 years; smaller oil fields have been discovered in the Lower Cretaceous carbonates of South Florida. The Sunniland field is the best known of these Florida fields. In South Texas, several small oil fields (Luling, Darst Creek, Larremore, Salt Flat, Imogene) have been discovered in dolomitized shelf-lagoon carbonates related to up-to-the-basin faults, and economically marginal gas fields have been discovered along the shelf edge (Deep Edwards Trend).

Throughout this Lower Cretaceous shelf area, water depths ranged from a few feet to one or two hundred feet and warm-water marine organisms flourished. A number of papers describe these shelf carbonates of Texas; notable among them are those by Fisher and Rodda (1969), Lozo and others (1959), and Rose (1972). Along a narrow band on the basinward edge of this broad shelf, biogenic growth climaxed and a complex of reefs, banks, bars, and islands developed. These Lower Cretaceous shelf-margin carbonates attained a thickness of 2,000 to 2,500 feet and have been identified as an almost continuous belt around the entire Gulf of Mexico; this report deals specifically with the Lower Cretaceous shelf-margin carbonates of the Stuart City Trend in the deep subsurface of South Texas (fig. 1).

Until 1954 only a few wildcat wells had been drilled along the Stuart City Trend (then known as the Deep Edwards Trend) and those had been in McMullen and LaSalle Counties where the top of the Edwards is less than 12,000 feet deep. The Stuart City field was discovered in 1954, when the Stanolind No. 1 Martin well was drilled. According to Holden (1963), the discovery of this field triggered a surge in exploration and drilling which lasted until 1962 and resulted in the drilling of 45 wildcat wells and the discovery of 16 fields. From 1962 on, drilling activity has declined considerably with two or fewer wells being drilled per year; it is important to note also that most of the more recent wells were drilled deeper to test Sligo carbonates and many have been completed uphole in the Wilcox sandstones.

Gas and some condensate have been produced from 8 of the 20 wells from which cores were studied (table 1); five of these wells are still producing. Initial production from these wells ranged from 3 to 15 million cubic feet of gas per day, and cumulative production ranges from 200 million to 2.1 billion cubic feet of gas. These low production figures, coupled with the greater depth to top of the Stuart City Formation northward along the trend (17,000 feet in Waller County), have not encouraged rapid exploration.

Objectives

The Stuart City Trend has been known and delineated for at least 20 years; geologists from several oil companies have carried on research studies on various portions of this trend and to varying degrees of detail. However, very little of the information obtained from these studies has

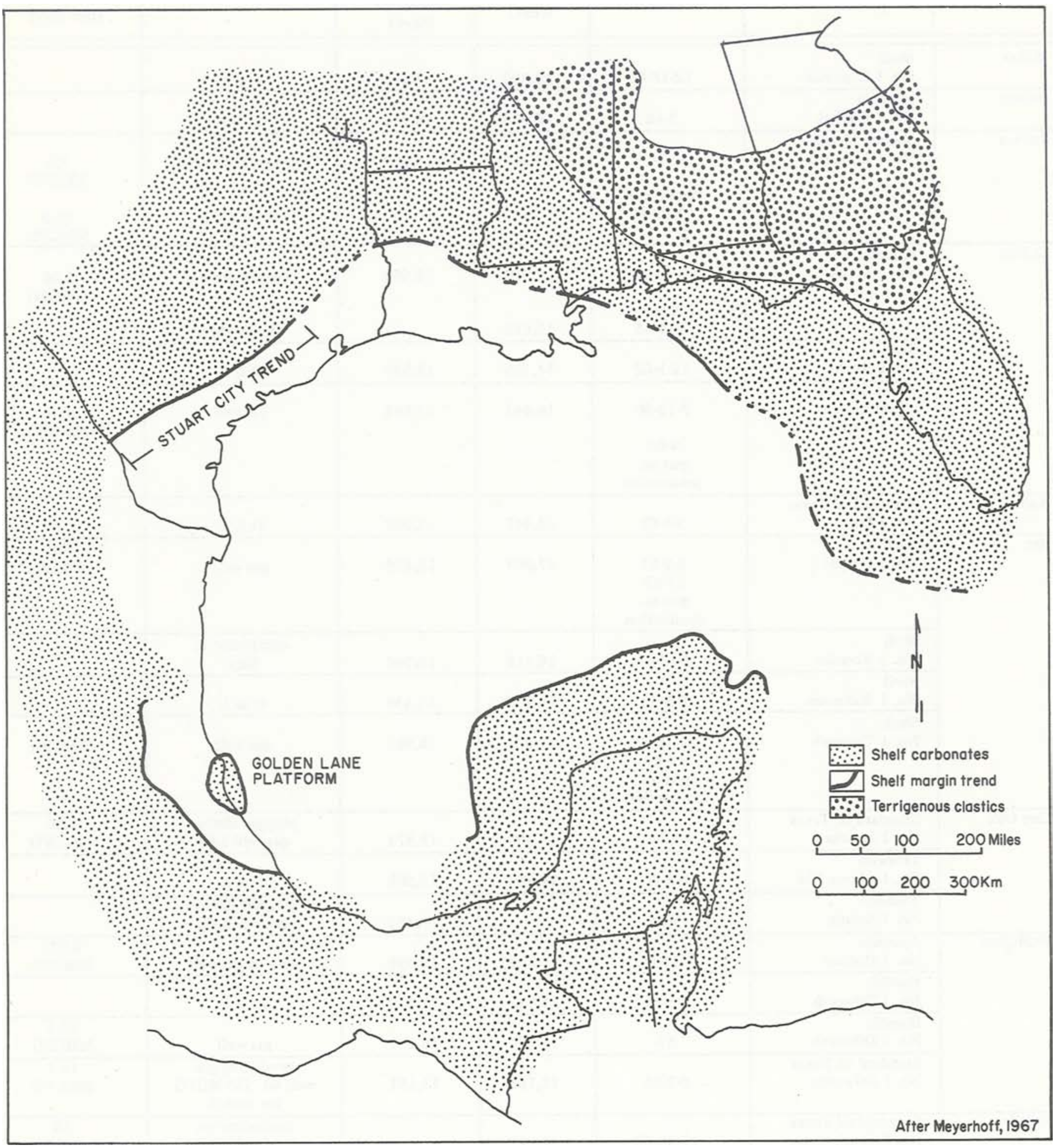


Figure 1. Distribution of Lower Cretaceous shelf-margin facies around the Gulf of Mexico. After Meyerhoff, 1967.

Table 1. Drilling and production data from wells along the Stuart City Trend from which core was examined.

County	Well Name	Date Completed	Total Depth (feet)	Depth to Top of Edwards (feet)	Well Status	Initial Production (per day)
Waller	Shell No. 1 Chapman	12-18-61	20,800	17,141	D & A	
Austin	Mitchell No. 1 Peschel	3-65	16,614	16,242	D & A	
Lavaca	Socony Mobil No. 1 Kahanek	3-11-60 Workover 11-23-60	14,361	13,260	plugged gas well Sept. 1971	3.6 MMCFG 15.0 MMCFG
DeWitt	Atlantic No. 1 Smith	7-26-62 Workover 7-15-65	15,910 15,910	13,650	plugged gas well March 1966	3.05 MMCFG
	Shell No. 1 Roehl	12-1-62	14,705	13,970	D & A	
	Texas Eastern Transmission No. 1 Garbe	9-14-60 9-63 put on production	14,841	13,845	gas well	8.6 MMCFG
Karnes	Standard of Texas No. 1 Pace	3-8-62	14,447	13,040	D & A	
Bee	Shell No. 1 O'Neal	6-2-61 11-67 put on production	17,004	13,472	gas well	7.8 MMCFG
	Shell No. 1 Roessler	4-12-67	16,118	13,700	completed in Sligo	
	Shell No. 1 Ruhmann	9-3-62	14,005	13,430	D & A	
	Shell No. 1 Tomasek	11-16-61 11-67 put on production	15,395	13,380	gas well	6.7 MMCFG
Live Oak	Standard of Texas No. 1 Isaacks	9-25-57	13,800	12,474	plugged shut-in gas well 2-63	1.35 MMCFG
	Tenneco No. 1 Alamo Lbr.	8-9-61	14,764	13,308	D & A	
	Tenneco No. 1 Schulz	5-62		13,452	plugged shut-in gas well 5-66	
McMullen	Amerada No. 1 Horton	7-17-56	11,854	11,526	shut-in gas well	2.225 MMCFG
	Humble No. 1 Dilworth	8-9-55	11,915	11,172	D & A	
	Humble No. 2 Dilworth	57	11,471	10,611	gas well	36.5 MMCFG
	Standard of Texas No. 1 Dilworth	2-2-55	12,758	11,151	producing gas well 65, 535 MCFG per month	11.3 MMCFG
LaSalle	Standard of Texas No. 1 South Texas Syndicate	11-30-52	11,525		producing gas well 24, 302 MCFG per month	10 MMCFG
	Stanolind No. 1 Martin	2-2-54	11,019	10,028	gas well	4.75 MMCFG

cum. prod. = cumulative production
#= pounds per square inch
D & A = dry and abandoned

bbls. cond. = barrels of condensate
MMCFG = million cubic feet of gas
MCFG = thousand cubic feet of gas

Perforated Interval	Treatment	Gas-Oil Ratio	Shut-In Pressure	Bottom Hole Temperature	Cumulative Production
	acidized and fractured			422°F.	
				334°F.	
13,320-14,278 13,320-14,278	acidized and fractured	14,200 120	3822# 5135#	315°F.	Cum. prod. 2,100 MMCFG + 24,850 bbls. cond.
13,640-13,884	acidized	22,650	2765#		Cum. prod. 37 MMCFG + 1,342 bbls. cond.
13,881-13,910	acidized	568	4117#	314°F.	Cum. prod. 878 MMCFG + 2,000 bbls. cond.
13,671-13,873	acidized	dry	4434#		Cum. prod. 892 MMCFG
				350°F.	
13,408-13,900		dry	4505#		Cum. prod. 1,100 MMCFG
12,456-12,736	acidized		2695#		
11,520-11,585	acidized	105,000	3667#		
	acidized				
		175,000	4255#		
11,170-11,270					Cum. prod. to 8-1-73 12,800 MMCFG + 167 bbls. cond.
10,258-10,346		445,000	3855#		Cum prod. to 8-1-73 288 MMCFG
10,092-10,120		dry	3816#		

been made available to those outside of the companies which carried on the work. Consequently, the first objective of this study was to bring together all the cores still available from the Stuart City Trend, study them in detail, and summarize our present knowledge of the depositional facies and environments of this classic trend. The Stuart City is an important model of shelf-edge carbonate deposition along a slowly and somewhat continuously subsiding basin. Knowledge of this trend should aid in better understanding the Lower Cretaceous carbonate depositional pattern around the entire Gulf of Mexico and along similar basins elsewhere in the world.

In recent years, knowledge of carbonate diagenetic processes and their effects on the development or preservation of primary and secondary carbonate porosity has increased tremendously. The second objective of this study was to apply these concepts to the study of the cores from the Stuart City Trend in an attempt to identify the primary and secondary porosity types and the diagenetic processes which affected porosity formation and preservation. Hopefully, clues which will lead to the discovery of zones of higher porosity elsewhere along the trend will come from a better knowledge of these important diagenetic processes.

A depositional-diagenetic model of the Lower Cretaceous shelf-margin trend should be important for further exploration along the Albian-Cenomanian Stuart City Trend in South Texas and the East Texas carbonates of the same age. An understanding of this part of the section, from which there is a relatively large amount of data, is essential for exploration along the older Aptian-age Sligo shelf-edge trend, from which there is much less control and where exploration activity is higher.

Paleogeographic Setting—South Texas

During the Early Cretaceous Albian, the broad carbonate shelf was separated from the open-marine environment of the Gulf by the shelf-margin sediments—commonly called the Stuart City Trend (fig. 2). The position of the trend with respect to the broader continental shelf and underlying Sligo shelf is best illustrated on the seismic section (fig. 3). This section crosses the Stuart City Trend in the southern part of the area of study where the trend is located more than 25 miles landward of the older Sligo shelf margin. The limestone making up this shelf-margin complex, the Stuart City Formation (fig. 4), is composed of reef and bank carbonates constructed primarily of rudist pelecypods, and of various types of carbonate sand bodies. Rudists are a group of sessile pelecypods in which one valve was enlarged or elongated and the other was smaller and served as a cap or lid. There are a number of different types of rudists; those important for this study include requienids (toucasids and another unidentified type), caprinids, and radiolitids (fig. 5). Other organisms which aided the rudists in forming the boundstones of the shelf edge are encrusting algae, encrusting bryozoans, the red algae *Solenopora*, stromatoporoids, and corals.

Dark-colored argillaceous carbonate mud and shale with planktonic foraminifers accumulated seaward or gulfward of the shelf margin. Landward of the shelf margin was a carbonate shelf greater than 400 miles wide. This shelf was divided into several distinct paleogeographical areas (fig. 2), primarily as a result of the major structural element—the San Marcos Arch (Fisher and Rodda, 1969; Rose, 1972). The arch is a remnant, low structure which trends perpendicular to the shelf edge; the Llano Uplift, which exposes rocks as old as Precambrian, is located in the center of this arch. Bedded nodular-mosaic and mosaic gypsum[2] and collapse breccias, interpreted as having resulted from the leaching of evaporites, occur on this structure; dolomite occurs around the fringes. Fisher and Rodda (1969) conclude that these sediments were deposited in the hypersaline Kirschberg Lagoon; Rose (1972) and Mueller and Loucks (1974), on the other hand, believe that the evaporites and dolomite were deposited on a supratidal salt flat or sabkha.

To the northeast, the Kirschberg Lagoon is bordered by the Comanche platform, a broad belt on which very shallow water conditions existed during the Early Cretaceous, and abundant shoal-water rudist patch reefs and associated grain bodies accumulated. Farther to the northeast, water depth gradually increased into the North Texas-Tyler basin in which dark-colored, argillaceous mudstones accumulated.

Southwest of the Kirschberg Lagoon is the Devils River platform on which shallow water conditions existed during the Early Cretaceous; rudist reefs grew along the edge of the platform just before it dropped off into the slightly deeper water of the McKnight basin to the southwest. The

[2] Gypsum terminology is from Maiklem and others (1969).

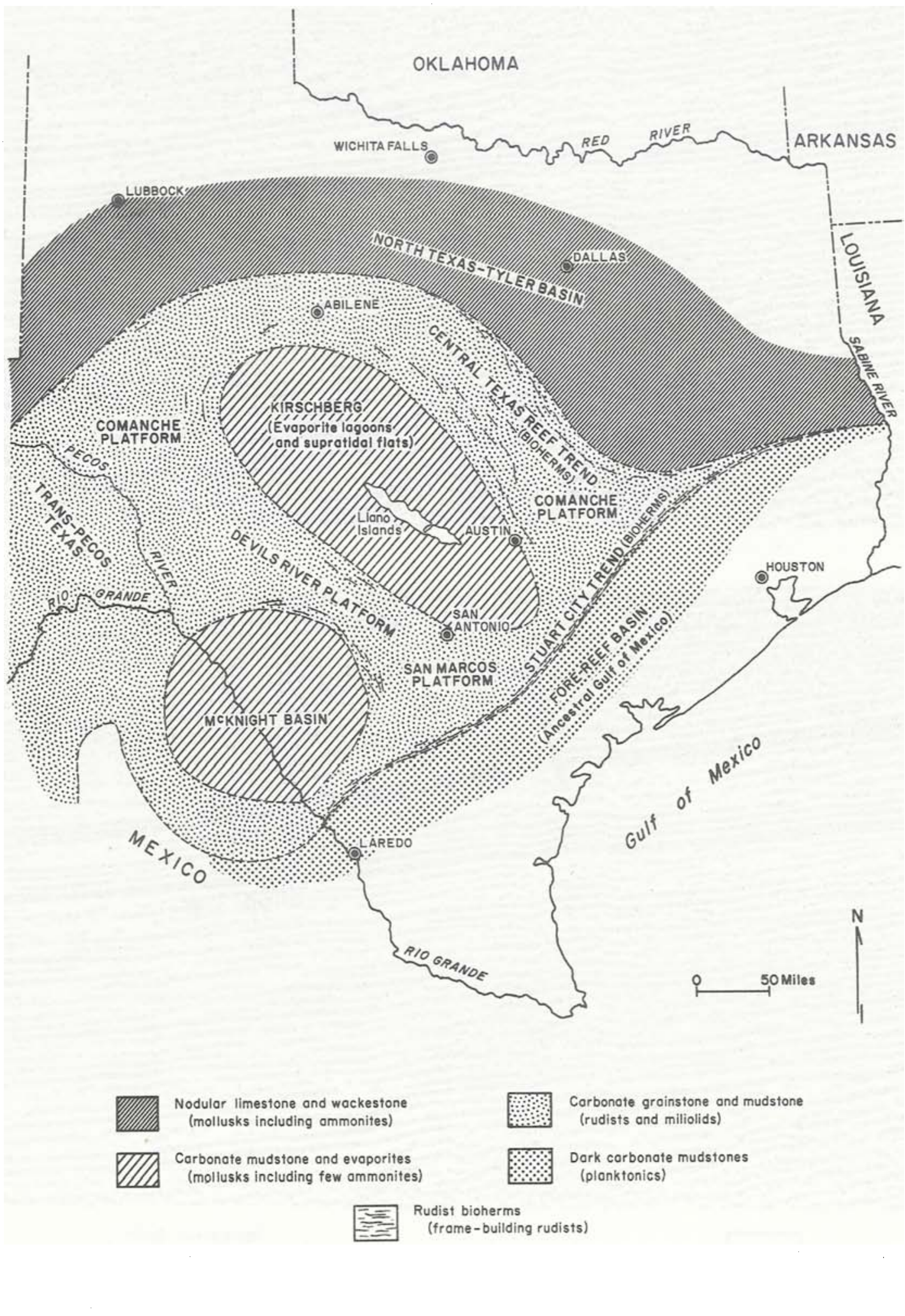
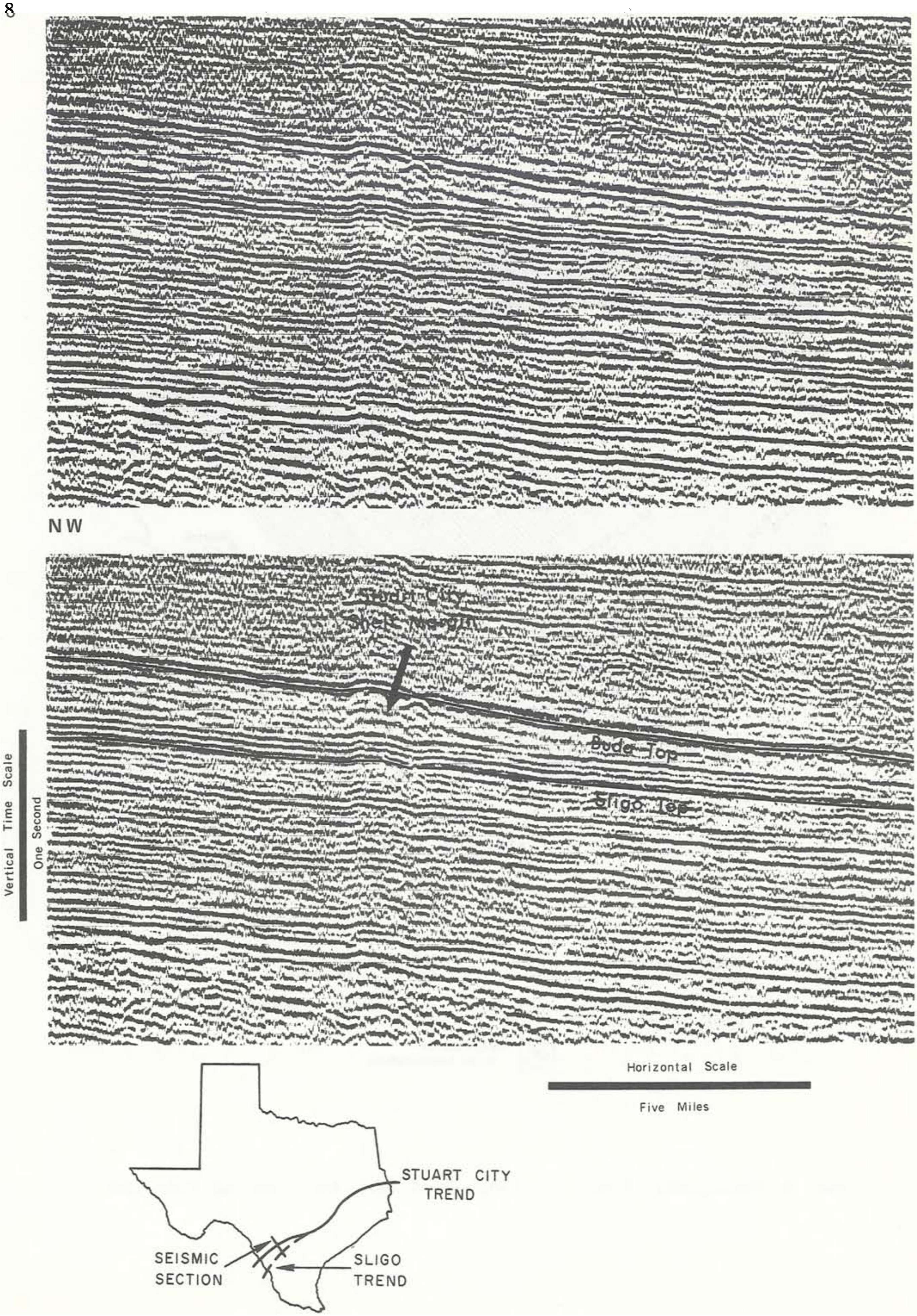


Figure 2. Paleogeography of the Lower Cretaceous of Texas. After Fisher and Rodda, 1969.


NW
Stuart City
Shelf Margin
Buda Top
Sligo Top
Vertical Time Scale
One Second
Horizontal Scale
Five Miles
STUART CITY TREND
SEISMIC SECTION
SLIGO TREND

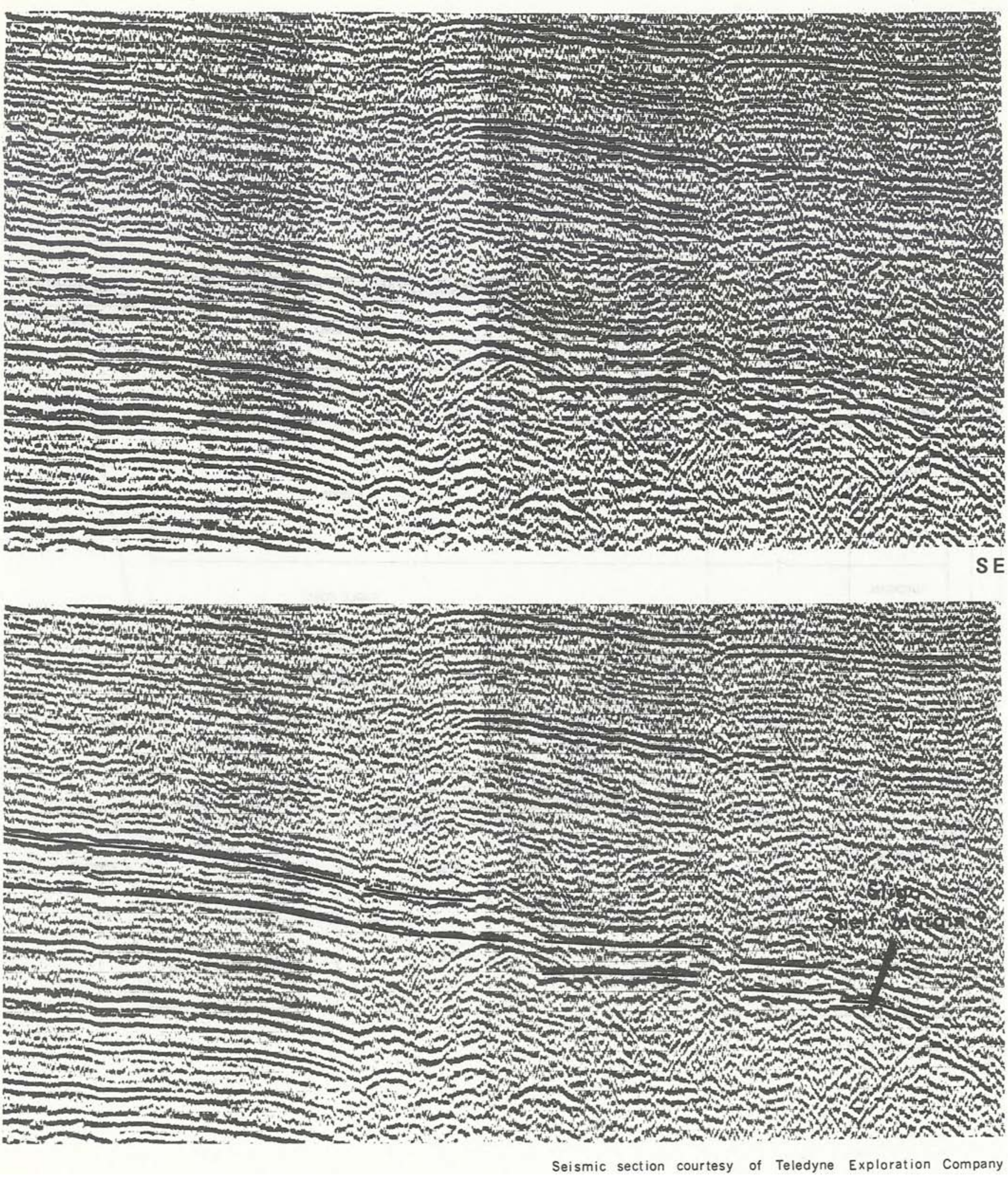


Figure 3. Seismic section across the Stuart City and Sligo shelf margins in the southern part of the study area. The section is shown at top without interpretations. The same section at the bottom shows the location of the Stuart City and Sligo shelf margins and the tops of the Buda (approximately one cycle above the top of the Stuart City Limestone) and the Sligo. Interpretations on this section were provided by John B. Sangree, Exxon Company, USA.

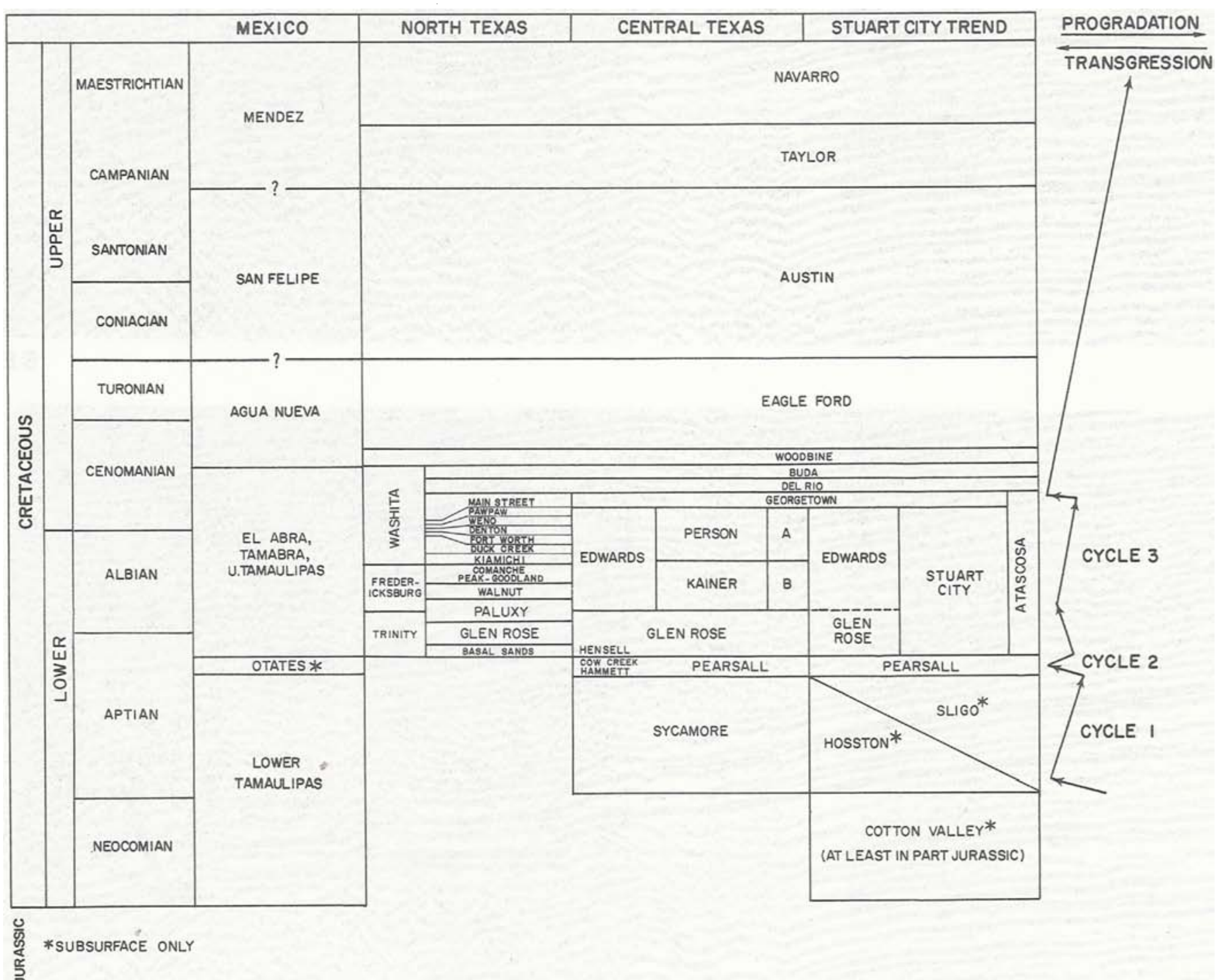


Figure 4. Correlation of Lower Cretaceous formations, western Gulf of Mexico. After Coogan, 1973; Coogan and others, 1972; Rose, 1972; Stricklin and others, 1971; Winter, 1961; and Young, 1972.

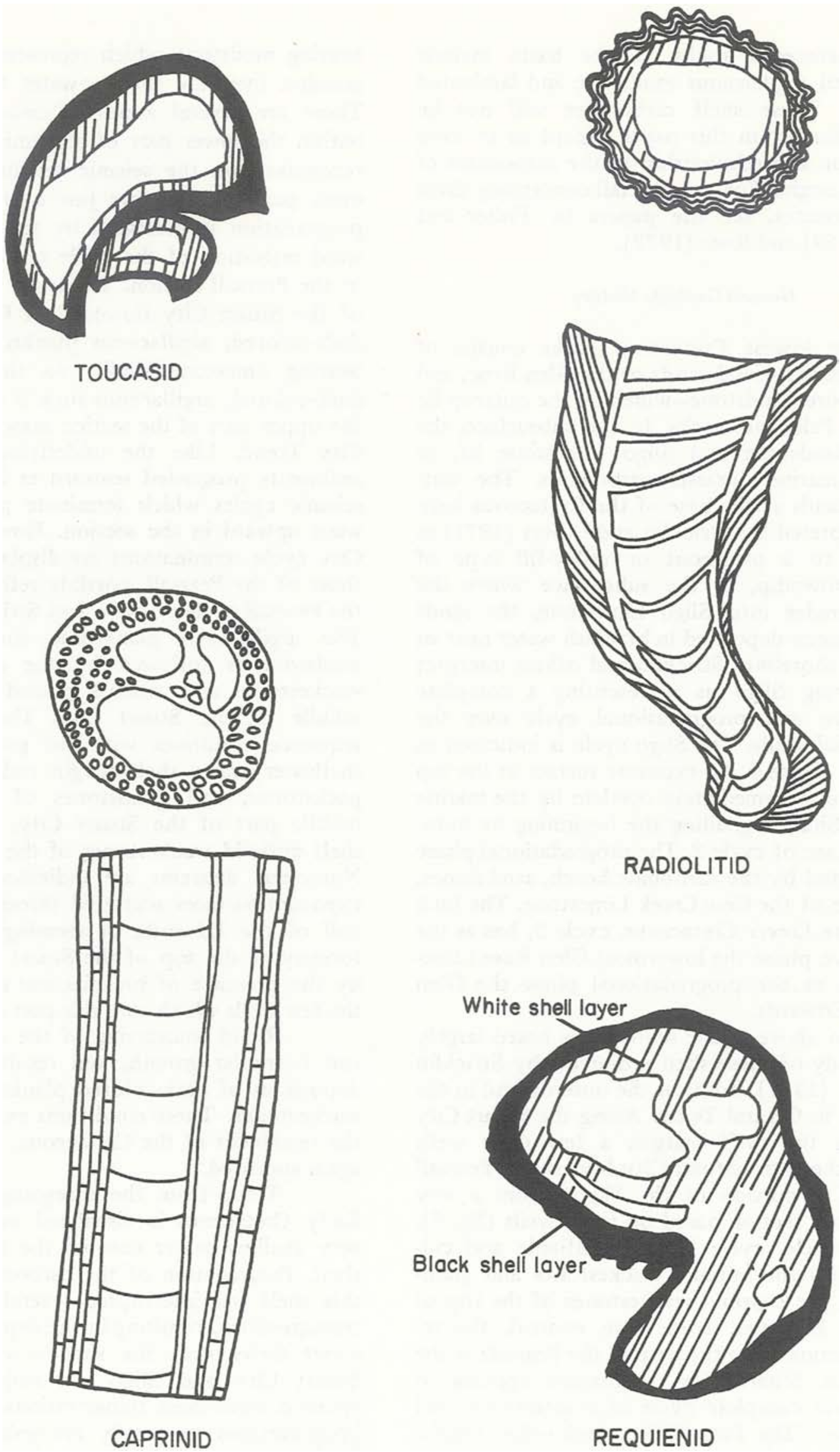


Figure 5. Rudist types which are significant contributors to the sediments of the Lower Cretaceous of South Texas.

Lower Cretaceous rocks in the basin include dark-colored argillaceous mudstone and laminated evaporites. These shelf carbonates will not be discussed further in this paper except as to their influence on and relationship to the carbonates of the shelf margin. For more detail concerning these shelf carbonates, see the papers by Fisher and Rodda (1969) and Rose (1972).

General Geologic History

The lowest Cretaceous rocks consist of quartzose sands—basal sands of the Glen Rose, and the Sycamore Sandstone—which on the outcrop lie on folded Paleozoic rocks. In the subsurface, the Hosston Sandstone and Sligo Limestone lie, in part, on marine Jurassic carbonates. The outcropping sands at the base of the Cretaceous have been interpreted by Stricklin and others (1971) as belonging to a piedmont or valley-fill type of deposit. Downdip, in the subsurface where the Hosston grades into Sligo Limestone, the sands may have been deposited in brackish water near an advancing shoreline. Stricklin and others interpret the overlying Sligo as representing a complete transgressive and progradational cycle over the basal alluvial sands. The Sligo cycle is indicated as cycle 1 on figure 4. An exposure surface at the top of the Sligo is immediately overlain by the marine Hammett Shale, signalling the beginning or transgressive phase of cycle 2. The progradational phase is represented by the carbonate beach, sand dunes, and caliche of the Cow Creek Limestone. The final cycle of the Lower Cretaceous, cycle 3, has as the transgressive phase the lowermost Glen Rose Limestone, and as the progradational phase the Glen Rose and Edwards.

The above cyclic sequence is based largely on the study of these shelf sediments by Stricklin and others (1971), both on the outcrop and in the subsurface in Central Texas. Along the Stuart City Trend, on the shelf margin, a few deep wells penetrate the entire Stuart City Limestone, Pearsall Shale, and a portion of the Sligo. From a very general cross section based on these wells (fig. 6), the Sligo cycle, cycle 1, is identifiable and culminates with the miliolid wackestones and grainstones and the caprinid wackestones of the top of the Sligo. However, from core control, the remaining section from the base of the Pearsall to the top of the Stuart City Formation appears to indicate one complete cycle of transgression and progradation. The Pearsall is a dark-colored dolomitic and argillaceous planktonic foraminifer-bearing mudstone which represents a rapid transgression over the shallow-water Sligo Limestone. There are several zones of oncolite wackestone within the lower part of this unit. The Pearsall is recognized on the seismic section (fig. 3) as the even, parallel reflectors just over the Sligo. The progradation is indicated by the progressive seaward migration of the cycle terminations upward in the Pearsall section. The lower quarter or more of the Stuart City (lower Glen Rose) consists of dark-colored, argillaceous planktonic foraminifer-bearing limestone similar to the Pearsall. This dark-colored, argillaceous rock is representative of the upper part of the section seaward of the Stuart City Trend. Like the underlying Pearsall, these sediments prograded seaward as indicated by the seismic cycles which terminate progressively seaward upward in the section. However, the Stuart City cycle terminations are displaced landward of those of the Pearsall, possibly reflecting the top of the Pearsall cycle or cycle 2 of Stricklin and others. The argillaceous planktonic foraminifer-bearing mudstone is followed by the echinoid-mollusk wackestones and mollusk grainstones toward the middle of the Stuart City. The progradational sequence continues with the gradation into the shallower water shelf-margin rudist wackestones, packstones, and grainstones of the upper and middle part of the Stuart City, and finally into shelf miliolid wackestones of the uppermost part. Numerous diastems are indicated by the minor exposure surfaces scattered throughout the upper half of the Edwards. A seemingly minor unconformity at the top of the Stuart City is indicated by the presence of breccias and solution zones in the few wells which core this part of the section.

Rapid foundering of the trend brought an end to rudist growth, and resulted again in the deposition of dark-colored planktonic foraminifer wackestones. These conditions existed throughout the remainder of the Cretaceous, and rudists never again appeared.

Thus, from the foregoing discussion, the Early Cretaceous is visualized as a period when very shallow water covered the broad, carbonate shelf. Progradation of the carbonate facies across this shelf was interrupted several times by major transgressions, resulting in the deposition of deeper water facies over the shallow-water facies. The Stuart City and Sligo are major cycles which resulted from these transgressions, and subsequent progradations are easily recognizable within the shelf-edge carbonates; cycles of less magnitude,

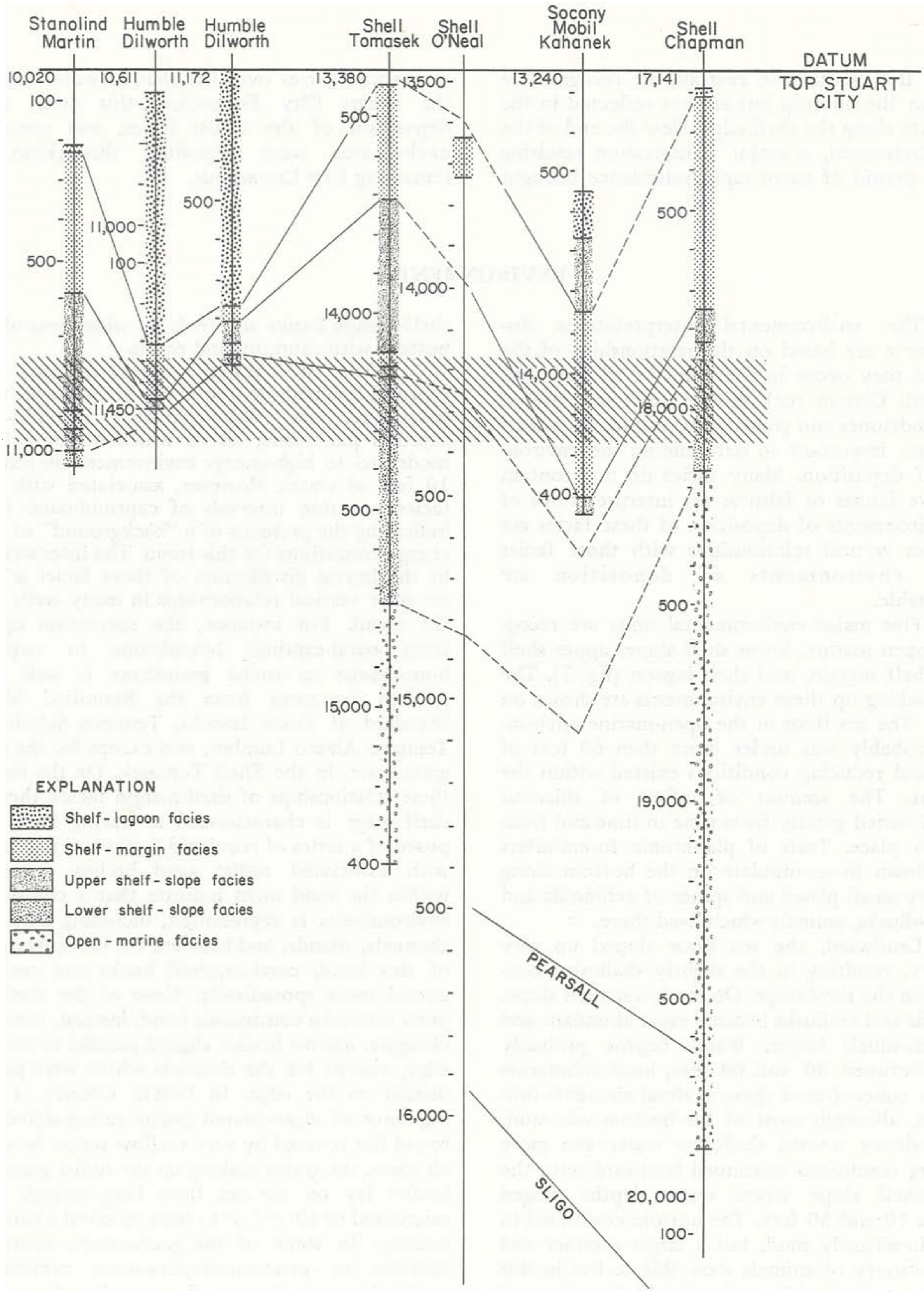


Figure 6. Facies sequence in the deep-penetrating wells along the Stuart City Trend. The outcrop formations—Edwards and Glen Rose—cannot be distinguished by carbonate facies types or by induction-electrical logs here on the shelf margin because of the progradational nature of this part of the section. The general location of this contact is based on the occurrence of *Orbitolina* and *Coskinolina* (generally considered typical of Glen Rose) and is shown by the broad hachured zone in the upper third of the section. The facies patterns do not parallel this time surface but rather are related to the position of the well with respect to the shelf edge. Therefore, log picks which generally reflect facies changes will be lower in wells landward of the shelf edge and higher in wells toward the shelf edge.

such as that within the Pearsall, are recognizable updip on the outcrop but are not reflected in the sediments along the shelf edge. Near the end of the Early Cretaceous, a major transgression resulting from a period of more rapid subsidence brought deep-water facies over the shallow-water facies of the Stuart City Formation; this event ended deposition of the rudist facies, and open-shelf carbonates were deposited throughout the remaining Late Cretaceous.

ENVIRONMENTS

The environmental interpretations discussed here are based on the relationships of the facies as they occur in the cores of all the wells examined. Certain rock fabrics, such as many of the boundstones and grainstones, and faunal associations are important in determining the environment of deposition. Many facies do not contain definitive faunas or fabrics; the interpretations of the environments of deposition of these facies are based on vertical relationships with those facies whose environments of deposition are recognizable.

Five major environmental units are recognized: open marine, lower shelf slope, upper shelf slope, shelf margin, and shelf lagoon (fig. 7). The facies making up these environments are shown on table 2. The sea floor in the open-marine environment probably was under more than 60 feet of water, and reducing conditions existed within the sediment. The amount of influx of siliceous material varied greatly from time to time and from place to place. Tests of planktonic foraminifers rained down to accumulate on the bottom along with very small plates and spines of echinoids and small mollusks, animals which lived there.

Landward, the sea floor sloped up very gradually, resulting in the slightly shallower conditions on the shelf slope. On the lower shelf slope, echinoids and mollusks became more abundant and the individuals larger. Water depths probably ranged between 30 and 60 feet; local submarine currents concentrated these skeletal elements into channels, although most of the bottom was mud. The tendency toward shallower water and more oxidizing conditions continued landward onto the upper shelf slope where water depths ranged between 10 and 50 feet. The bottom continued to be predominantly mud, but a larger number and greater variety of animals were able to live in this area. The most significant fauna added to those of the lower shelf slope are caprinid rudists and branching and massive corals. Locally, patch reefs or banks composed of corals and stromatoporoids grew. These patch reefs were isolated from the shelf-margin banks and reefs by wide areas of mud bottom with caprinids and corals.

The shelf-margin facies include coral-caprinid boundstone, requienid boundstone, rudist grainstone, and algae-encrusted miliolid-coral-caprinid packstone, all of which accumulated in moderate- to high-energy environments in less than 10 feet of water. However, associated with these facies are thin intervals of caprinid-coral facies, indicating the presence of a "background" of lower energy conditions for this trend. The interpretation of the lateral distribution of these facies is based on their vertical relationships in many wells along the trend. For instance, the succession upward from coral-caprinid boundstone to requienid boundstone to rudist grainstone is well documented in cores from the Stanolind Martin, Standard of Texas Isaacks, Tenneco Schulz, and Tenneco Alamo Lumber, and except for the rudist grainstone, in the Shell Tomasek. On the basis of these relationships of shelf-margin facies, then, the shelf edge is characterized as having been composed of a series of requienid banks and patch reefs with associated rudist sand bodies. Structures within the sand units indicate that a complex of environments is represented, including bars, tidal channels, islands, and beaches. On the seaward side of this band, coral-caprinid banks and reefs occurred more sporadically. None of the shelf-edge units formed a continuous band; instead, they were elongate, narrow bodies aligned parallel to the shelf edge, except for the channels which were perpendicular to the edge. In DeWitt County, a thick sequence of algae-coated grains accumulated on a broad flat covered by very shallow water. In almost all cases, the grains making up the rudist grainstone bodies lay on the sea floor long enough to be micritized or altered or to have received a thin algal coating. In some of the grainstones, contemporaneous or penecontemporaneous cementation took place on the sea floor or just beneath it, resulting in the development of fibrous to bladed isopachous rim cement. Subaerial cementation took place in the vadose zone or along active beaches in the surf zone; this resulted in the

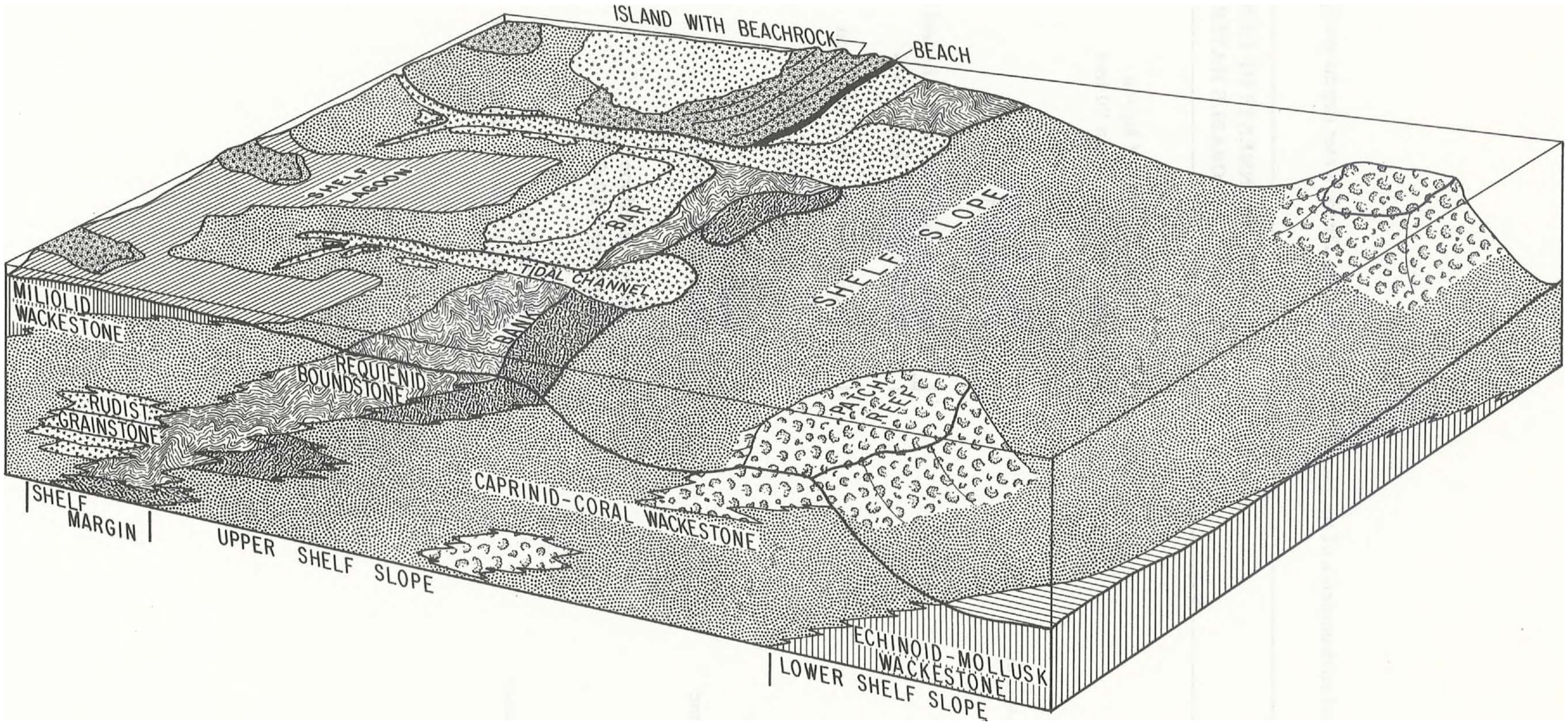


Figure 7. Facies and interpreted depositional environments across the Stuart City Trend, South Texas.

Table 2. Depositional environments of the facies of the Stuart City Trend. Water depths are inferred.

FACIES	ENVIRONMENTS OF DEPOSITION AND PROBABLE WATER DEPTH	
Miliolid wackestone Mollusk wackestone Toucasid wackestone Mollusk-miliolid grainstone	Shallow-water shelf lagoon Water depth less than 20 feet	
Algae-encrusted miliolid-coral-caprinid packstone	Stable grain flat Water depth 1-5 feet	SHELF MARGIN
Rudist grainstone	Beaches, tidal bars, spits, channel fill Water depth less than 10 feet	SHELF MARGIN
Requienid boundstone Coral-caprinid boundstone	Reefs and banks—low relief and discontinuous Water depth 5-15 feet	SHELF MARGIN
Caprinid-coral wackestone Coral-stromatoporoid boundstone	Upper shelf slope Water depth 10-30 feet	
Intraclast grainstone Echinoid packstone Echinoid-mollusk wackestone	Lower shelf slope Water depth 30-60 feet	
Planktonic foraminifer wackestone	Open marine Water depth greater than 60 feet	

formation of beachrock typified by dark-colored, pendant dripstone cement. Both of these early cements—the isopachous and dripstone—were very thin, and despite their presence the porosity and permeability of the grainstones remained extremely high.

The shallow-water shelf-lagoon facies include miliolid wackestone, mollusk wackestone, toucasid wackestone, and mollusk-miliolid grainstone. The facies accumulated in shallow water (0 to 20 feet deep) and under low-energy conditions. Local variations in currents or bottom topography resulted in the formation of small islands typified by well developed birdseye structure; these islands were commonly fringed by mollusk grainstone bodies. Grapestone and crusts developed on broad, very shallow-water stable flats in areas protected from normal surf and tidal currents. Small channels served as passageways for the slow movement of sea water on and off the flats during tidal changes, but significant sediment transport took place on these flats only during major storms.

Cementation between grains, within voids in boundstone areas, and within body cavities of rudists and other mollusks occurred at several places in this environmental setting, but primarily within the facies of the shelf lagoon and shelf margin. Micrite rims, the result of both grain-edge alteration and algal coating, are present on all the skeletal fragments and intraclasts which make up the grain environments. These rims formed as the grains lay on the sea floor. Thin layers of fibrous to bladed isopachous cement were deposited within voids and between grains in facies which were accumulating in very shallow, warm water. Dripstone and meniscus cements were deposited within the sediments exposed to vadose or intertidal conditions on small, local islands. The micrite rims, isopachous cement, and dripstone and meniscus cement, however, make up a very small part of the final calcite cementation and merely served to partially lithify the sediment and protect it from later compaction.

After additional growth of the shelf margin, accompanied by slow subsidence of the shelf, these partially cemented sediments were buried to shallow depths. Leaching of aragonite and high-magnesium calcite shells took place. All voids were lined with thick layers of impure radiaxial cement deposited from phreatic-meteoric water. Later, after additional subsidence, the remaining voids were filled with equant calcite.

FACIES

General Remarks

Cores are the primary information source for any subsurface study of carbonate facies, environments, and diagenesis. More than 10,000 feet of core was obtained from 20 wells along this trend (fig. 8). Of secondary importance, but still necessary, are the induction-electrical logs. Although even significant variations in the carbonate fabric or texture commonly are not reflected on the logs, major breaks are normally readily identified, particularly when changes in lithology accompany these breaks. Thus, a log cross section (fig. 9) provides a gross framework into which the more detailed facies information from cores can be inserted. The spacing of the core control along the trend is shown on figure 8; the vertical location of the core in each well is shown on the induction-electrical log cross section on figure 9. Illustrations of the facies are shown on figures 10-26. The water depths indicated under Depositional Environment are obviously inferred. The position of each facies within the cored intervals is shown on the facies cross section (figs. 27-31).

Several categories under Facies Descriptions need further explanation. Under "Thickness" is included both the minimum and maximum occurrence of the facies. "Associated Facies" includes facies which are in contact either over or under the facies described. "Occurrence" includes only the wells in which a particular facies was found; for better location refer to the facies cross sections.

The nomenclature used in describing the porosity types is from Choquette and Pray (1970); the nomenclature and classification of primary cement and diagenetic calcite are from Folk (1965).

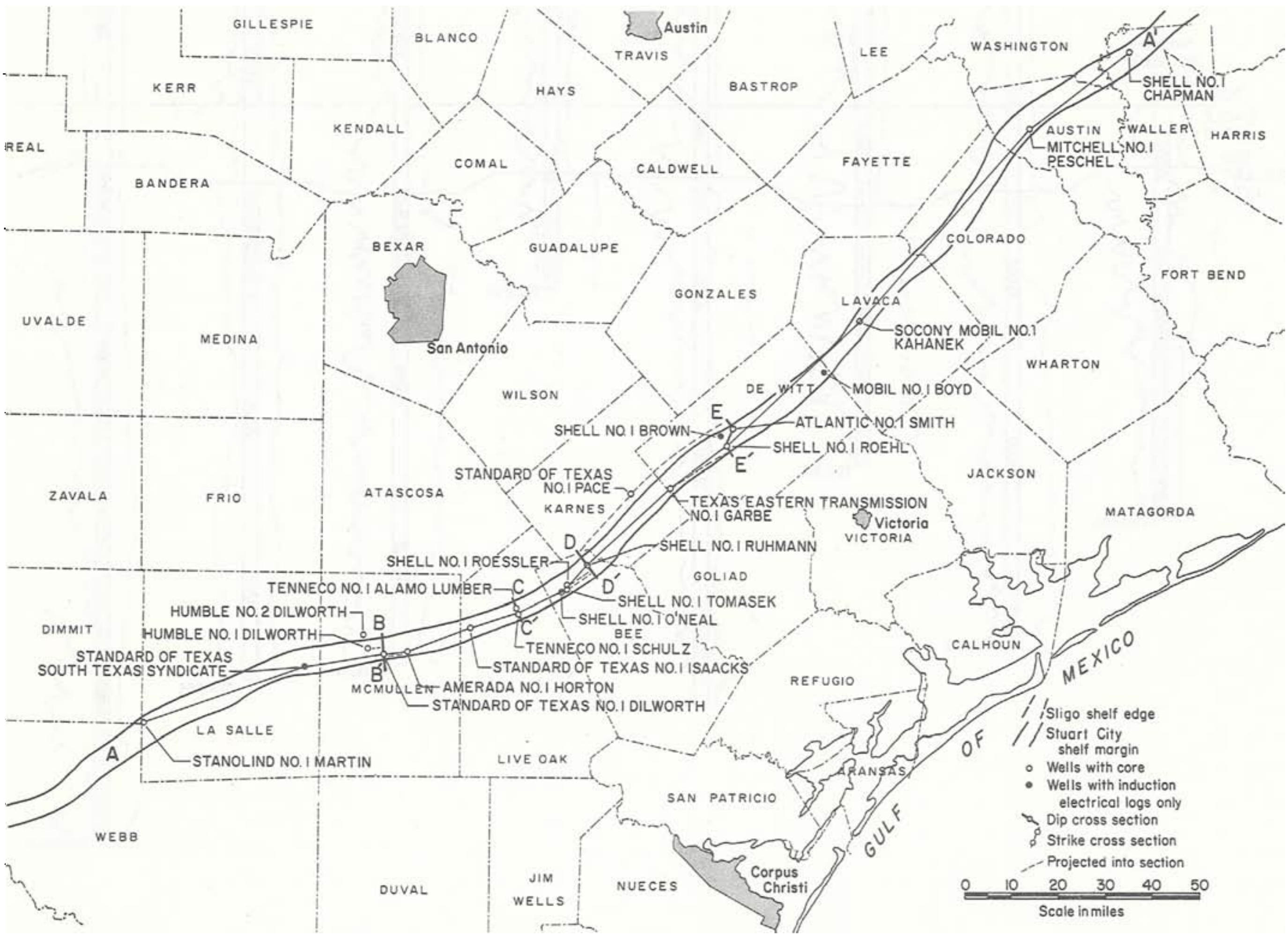


Figure 8. Stuart City Trend, South Texas, showing locations of the wells from which cores were obtained for this study.

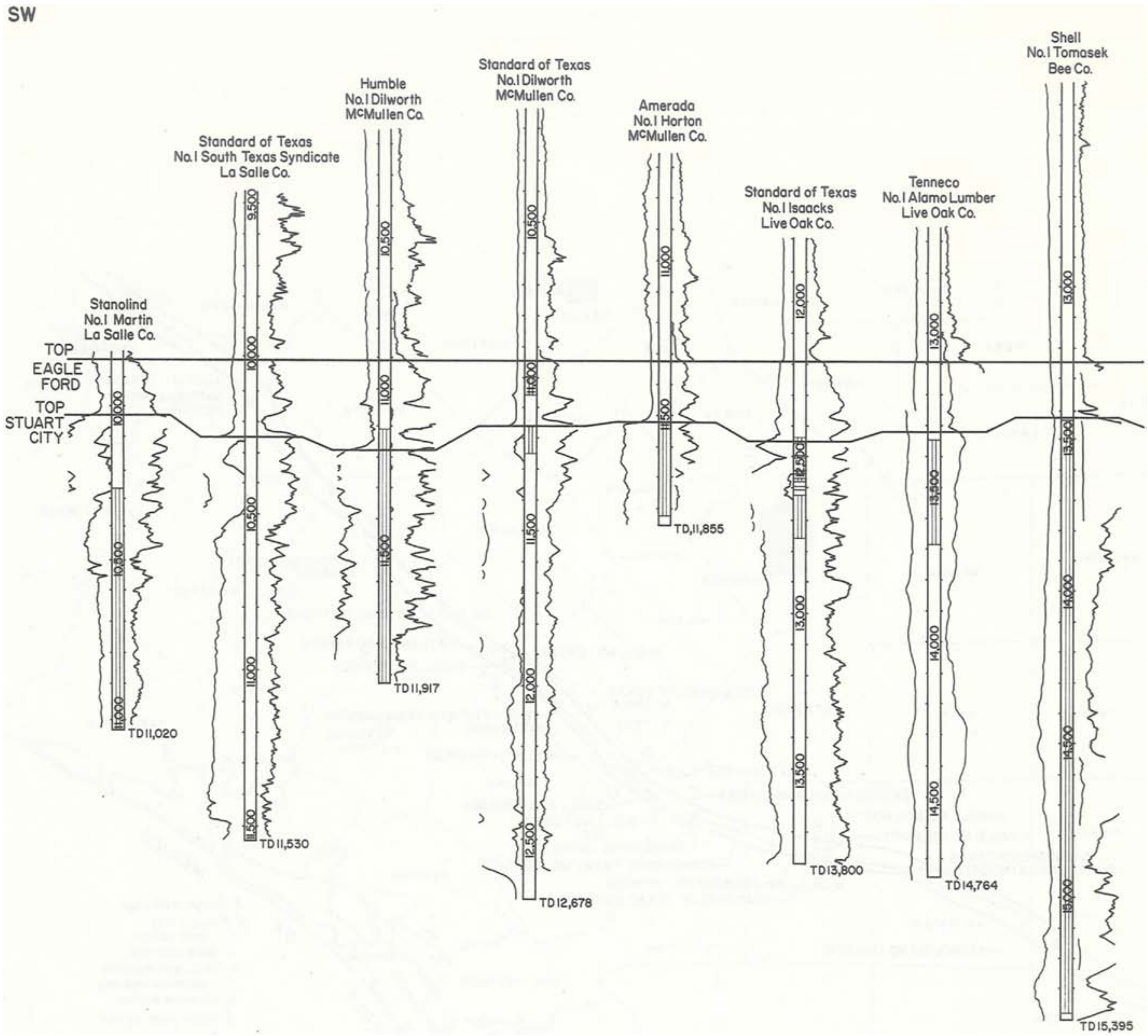
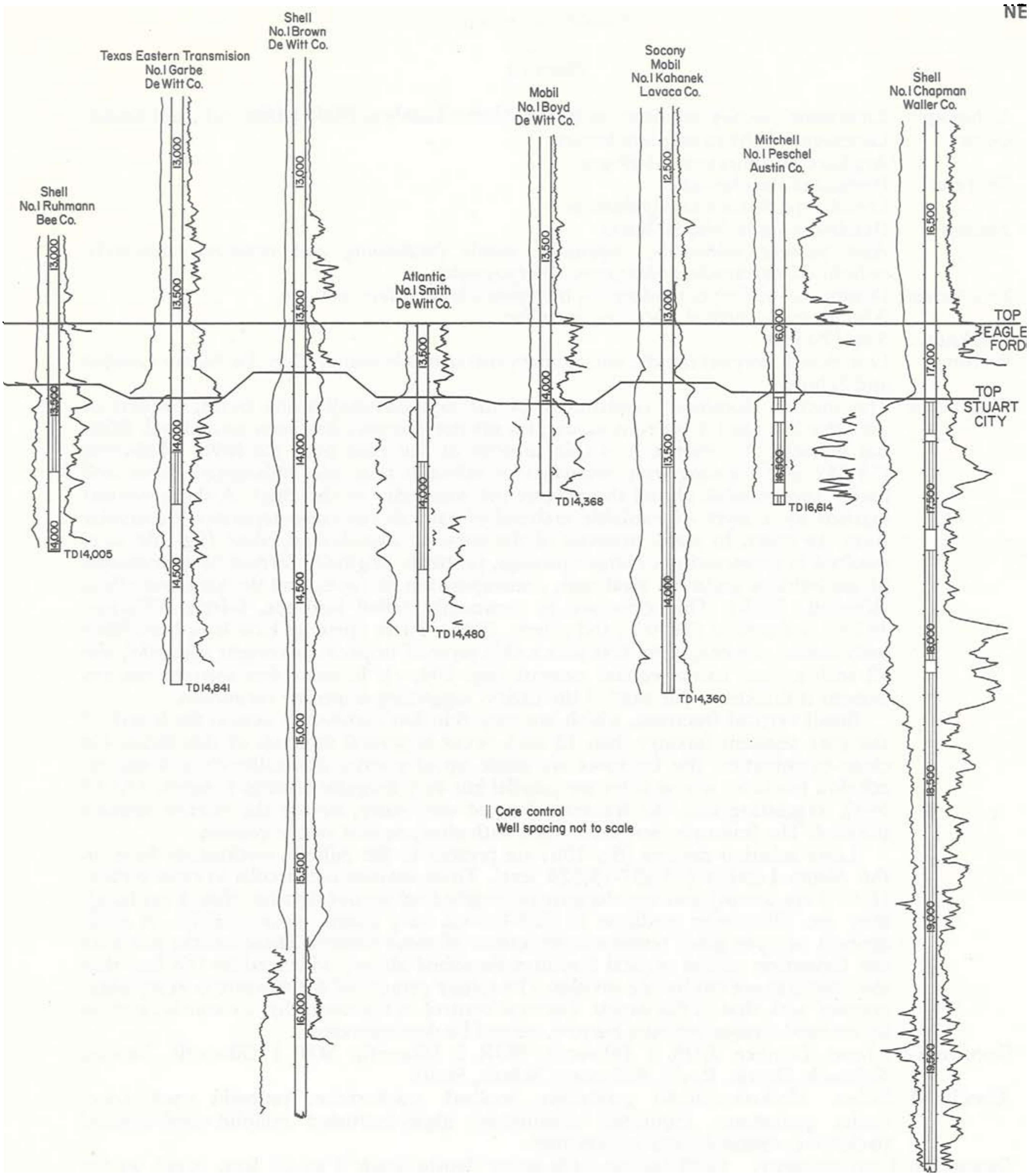


Figure 9. Induction-electrical log cross section along the Stuart City Trend, South Texas.


NE
Shell
No.1 Ruhmann
Bee Co.
Texas Eastern Transmision
No.1 Garbe
De Witt Co.
Shell
No.1 Brown
De Witt Co.
Atlantic
No.1 Smith
De Witt Co.
Mobil
No.1 Boyd
De Witt Co.
Socony
Mobil
No.1 Kahanek
Lavaca Co.
Mitchell
No.1 Peschel
Austin Co.
Shell
No.1 Chapman
Waller Co.
TOP
EAGLE
FORD
TOP
STUART
CITY
TD14,005
TD14,841
TD14,480
TD14,368
TD14,360
TD16,614
|| Core control
Well spacing not to scale

Facies Descriptions

Miliolid wackestone

Figure 10

Lithology: Limestone (locally argillaceous in the Alamo Lumber, HOR 1 Dilworth, and Smith)
Color: Limestone—light to medium brown
Argillaceous limestone—dark gray
Texture: Dominant—wackestone
Locally—packstone and grainstone
Fossils: Dominant—miliolids, mollusks
Also present—echinoids, caprinids, corals (branching and massive), toucasids, radiolitids, ostracods, *Solenopora*, *Dictyoconus*
Structures: Dominant—birdseye, mudcracks, burrows, irregular laminae
Also present—vertical fractures, stylolites
Thickness: 5 to 120 feet
Porosity: Less than 5 percent moldic and primary intraparticle scattered in the Alamo Lumber and Schulz
Diagenesis: The micrite, dominant constituent of the miliolid wackestone facies, consists of particles less than 3 microns across; no micrite porosity has been recognized. Silica has replaced the micrite in a thin interval of the core from the HOR 1 Dilworth (11,332 feet) leaving only remnants of miliolids near the replacement front and barely recognizable ghosts throughout the remainder of the chert. A sharp contact marked by a layer of insoluble material of variable thickness separates the micrite from the chert. In many intervals of the core, an algae-bound fabric (fig. 10c, d, e) resulted in preservation of large openings, probably originally formed by entrapment of gas bubbles under an algal mat, decomposition of roots, and the keystone effect (Kendall, 1969). This structure is commonly called birdseye, loferite (Fischer, 1964), or fenestral (Tebbutt and others, 1965). These openings have later been filled with calcite cement, some first with a thin layer of isopachous cement (fig. 10d) and all with a final coarse equant cement (fig. 10d, e). In some thin sections the rim cement is thicker on the roof of the cavity, suggesting dripstone formation.

Small vertical fractures, which are very thin but commonly extend the length of the core segment (greater than 15 cm), occur in several intervals of this facies. On close examination the fractures are made up of a series of smaller (3 to 4 cm) en echelon fractures whose sides are parallel but very irregular (Alamo Lumber, 13,517 feet), suggesting that the fractures formed very early, before the micrite became lithified. The fractures were later filled with clear, equant calcite cement.

Large solution cavities (fig. 10b) are present in the miliolid wackestone facies in the Alamo Lumber (13,507-13,526 feet). These cavities are circular in cross section (2 to 3 cm across) and are elongate in longitudinal section (greater than 8 cm long); they are filled with medium- to dark-brown, very coarse mosaic calcite. A small amount of open space remains in the center of some cavities. These cavities postdate the formation of the vertical fractures described above, evidenced by the fact that the fractures are cut by the cavities. The calcite cement of the fracture is in stylolitic contact with that of the cavity. Textural control of the cavity by the matrix, such as by textural change within a burrow, cannot be demonstrated.

Occurrence: Alamo Lumber, HOR 1 Dilworth, HOR 2 Dilworth, SOT 1 Dilworth, Isaacks, Kahanek, Martin, Roehl, Ruhmann, Schulz, Smith
Associated facies: Mollusk-miliolid grainstone, mollusk wackestone, toucasid wackestone, rudist grainstone, requienid boundstone, algae-encrusted miliolid-coral-caprinid packstone, caprinid-coral wackestone
Depositional environment: Shelf lagoon with water depths from 0 to 20 feet, based on the presence of a diverse fauna with dominant miliolids and mollusks and common sedimentary structures such as burrows and irregular laminae.

Birdseye and mudcracks indicate that low-relief islands occurred commonly throughout the area represented by this facies.

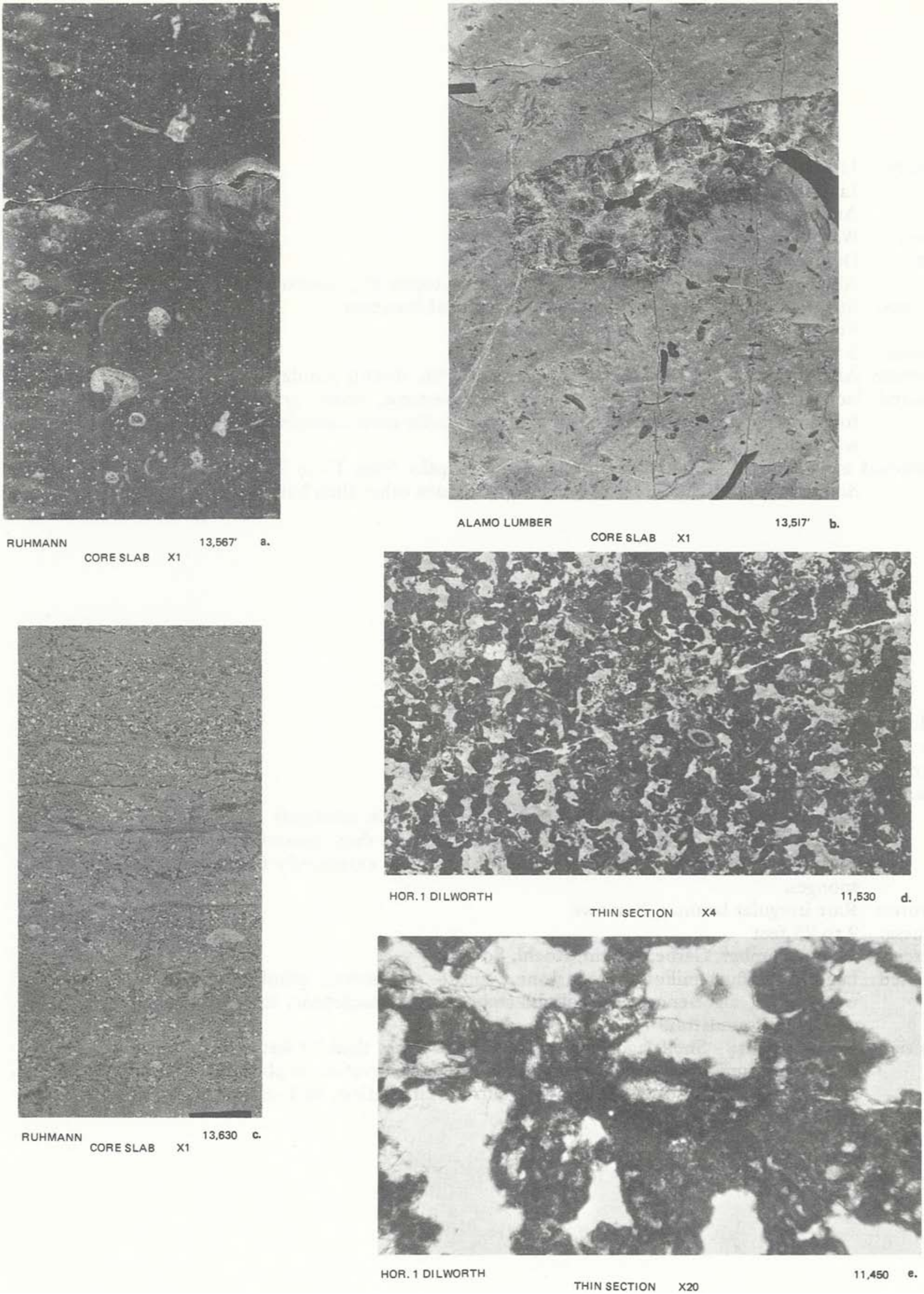


Figure 10. Miliolid wackestone. a. Miliolids (white specks) and gastropods in carbonate mud. b. Large solution cavity in miliolid wackestone. The cavity is filled with equant calcite (P.E). c. Laminated birdseye fabric. Original pores are filled with equant calcite (dark colored on photograph). d. Algae-bound fabric in birdseye interval. Irregular vugs were first lined with isopachous rim cement and finally filled with equant calcite. e. Algae-bound fabric in birdseye interval. Original pores are now filled with equant calcite.

Mollusk wackestone[3]

Figure 11a, b

Lithology: Limestone (locally argillaceous)
Color: Limestone—light brown
Argillaceous limestone—dark brown
Texture: Wackestone and packstone
Fossils: Dominant—mollusks
Also present—echinoids, miliolids, radiolitids, caprinids, ostracods, toucasids
Structures: Burrows, stylolites, geopetal structures, vertical fractures
Fractures are filled with spar and bitumen.
Thickness: 5 to 45 feet
Occurrence: Alamo Lumber, HOR 2 Dilworth, Garbe, Martin, Roehl, Schulz
Associated facies: Mollusk grainstone, toucasid wackestone, rudist grainstone, planktonic foraminifer wackestone, algae-encrusted miliolid-coral-caprinid packstone, miliolid wackestone, requienid boundstone
Depositional environment: Shelf lagoon with water depths from 10 to 20 feet, based on the dominant molluscan fauna and lack of structures other than burrows

Toucasid wackestone

Figure 11c, d

Lithology: Limestone (locally argillaceous)
Color: Light to medium brown
Texture: Wackestone
Fossils: Dominant—toucasid rudists
Also present—mollusks, caprinids, miliolids, ostracods, echinoids
Plant material is disseminated through the matrix as thin, discontinuous dark layers. Figure 11c shows a toucasid shell which has been extensively bored, probably by sponges.
Structures: Rare irregular laminae, burrows
Thickness: 9 to 23 feet
Occurrence: Alamo Lumber, Garbe, Martin, Roehl, Schulz
Associated facies: Mollusk-miliolid grainstone, rudist grainstone, planktonic foraminifer wackestone, algae-encrusted miliolid-coral-caprinid packstone, miliolid wackestone, requienid boundstone
Depositional environment: Shelf lagoon with water depths less than 10 feet. The presence of a restricted fauna of dominant toucasids and the preservation of plant material suggest accumulation in an area of restricted current circulation, such as on the lee side of an island.

[3] Mollusk is used here as excluding rudists.

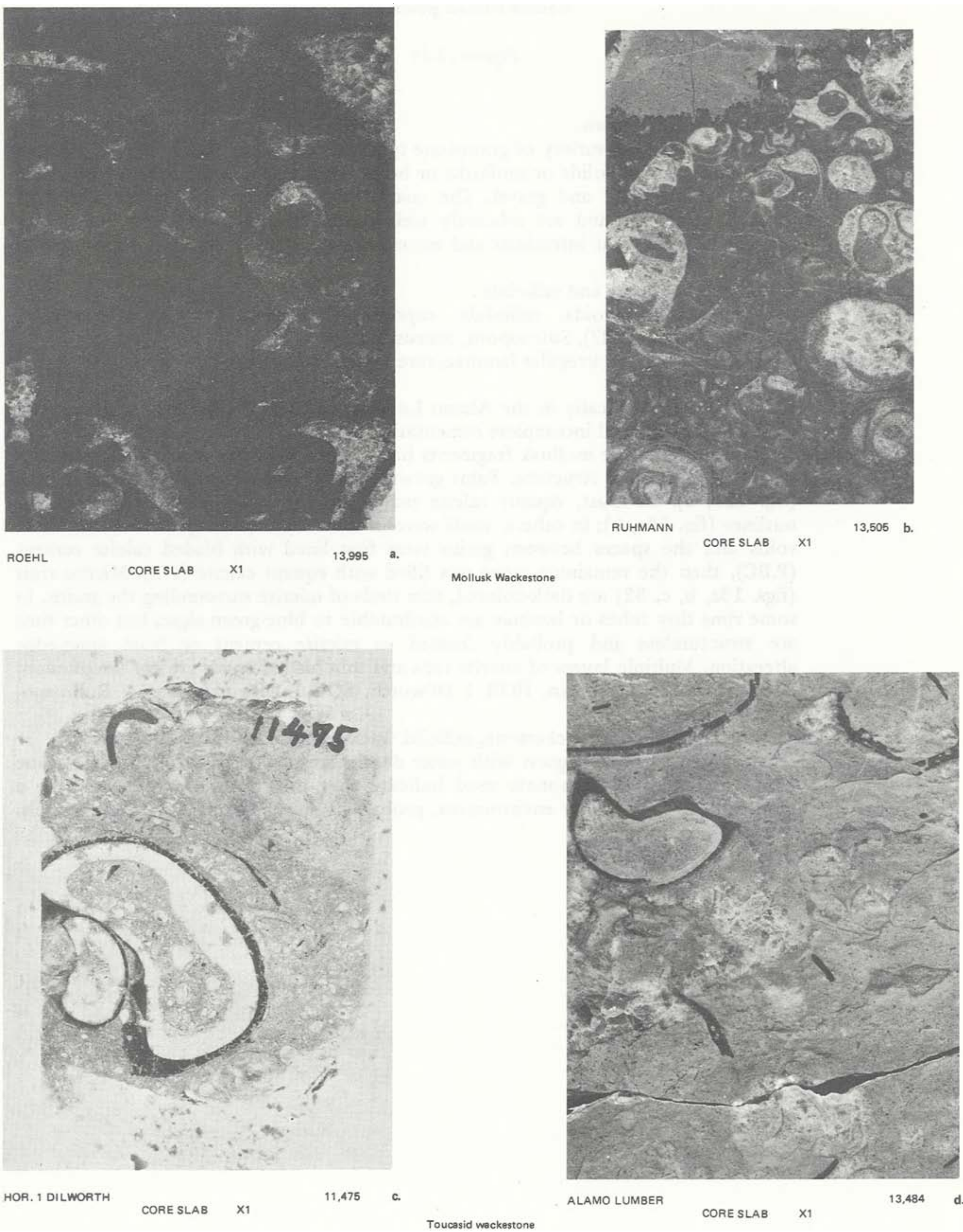
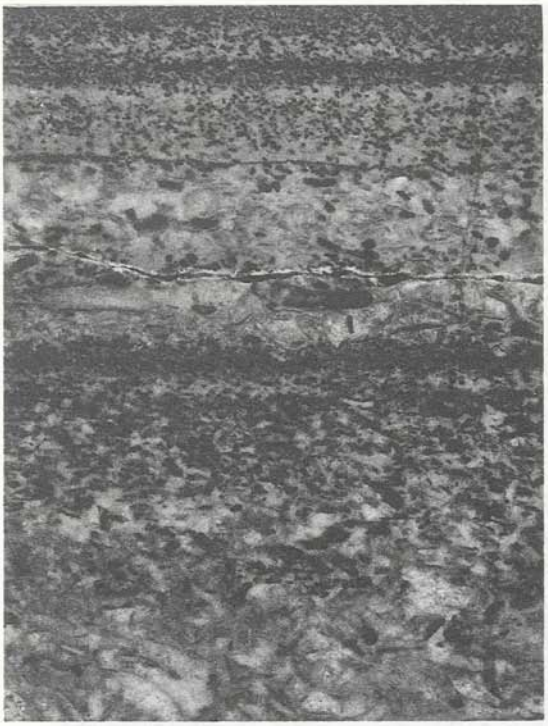


Figure 11. Mollusk wackestone. a. Dark-colored carbonate mud with large gastropods. b. Abundant gastropods in carbonate mud. Geopetal structures occur within the gastropods. Toucasid wackestone. c. Toucasid cross section showing cut of two whorls. Small borings are abundant on the upper surface. d. Typical kidney-bean shape of toucasid cross section. Matrix is carbonate mud.

Mollusk-miliolid grainstone

Figures 12-14

Lithology: Limestone
Color: Medium to light brown
Texture: Grainstone. A great variety of grainstone types is included in this facies, but all have either abundant miliolids or mollusks or both. Grain size ranges from very fine sand to very coarse sand and gravel. The coarser types commonly contain abundant mollusk fragments and are relatively well sorted (figs. 12, 13); the finer types contain miliolids and intraclasts and are commonly algae-bound and poorly sorted (fig. 14).
Fossils: Dominant—mollusks and miliolids
Also present—echinoids, miliolids, caprinids, toucasids, corals, *Dictyoconus*, *Orbitolina* (reworked?), *Solenopora*, encrusting algae
Structures: Horizontal, even and irregular laminae; rare vertical fractures
Thickness: 2 to 156 feet
Porosity: Up to 10 percent locally in the Alamo Lumber and HOR 1 Dilworth resulting from leaching of grains and incomplete cementation
Diagenesis: Neomorphism of the mollusk fragments has resulted in nearly complete destruction of the original shell structure. Faint growth laminae are discernable in some shells (fig. 12b, c). In most, equant calcite makes up the space within the fragment outlines (fig. 13a, b); in others, voids were produced by leaching of the shell. These voids and the spaces between grains were first lined with bladed calcite cement (P.BC), then the remaining space was filled with equant calcite (P.E). Micrite rims (figs. 13a, b, c, 32) are dark-colored, thin rinds of micrite surrounding the grains. In some rims tiny tubes or laminae are attributable to blue-green algae, but other rims are structureless and probably formed as micrite cement or from grain-edge alteration. Multiple layers of micrite rims and thin bladed crusts are not uncommon.
Occurrence: Alamo Lumber, Chapman, HOR 1 Dilworth, SOT 1 Dilworth, Garbe, Ruhmann, Schulz, Tomasek
Associated facies: Caprinid-coral wackestone, miliolid wackestone, mollusk wackestone
Depositional environment: Shelf lagoon with water depths from 0 to 10 feet. The grainstone fabric and lack of carbonate mud indicate that this facies was deposited in a moderate- to high-energy environment, probably around islands and tidal channels.

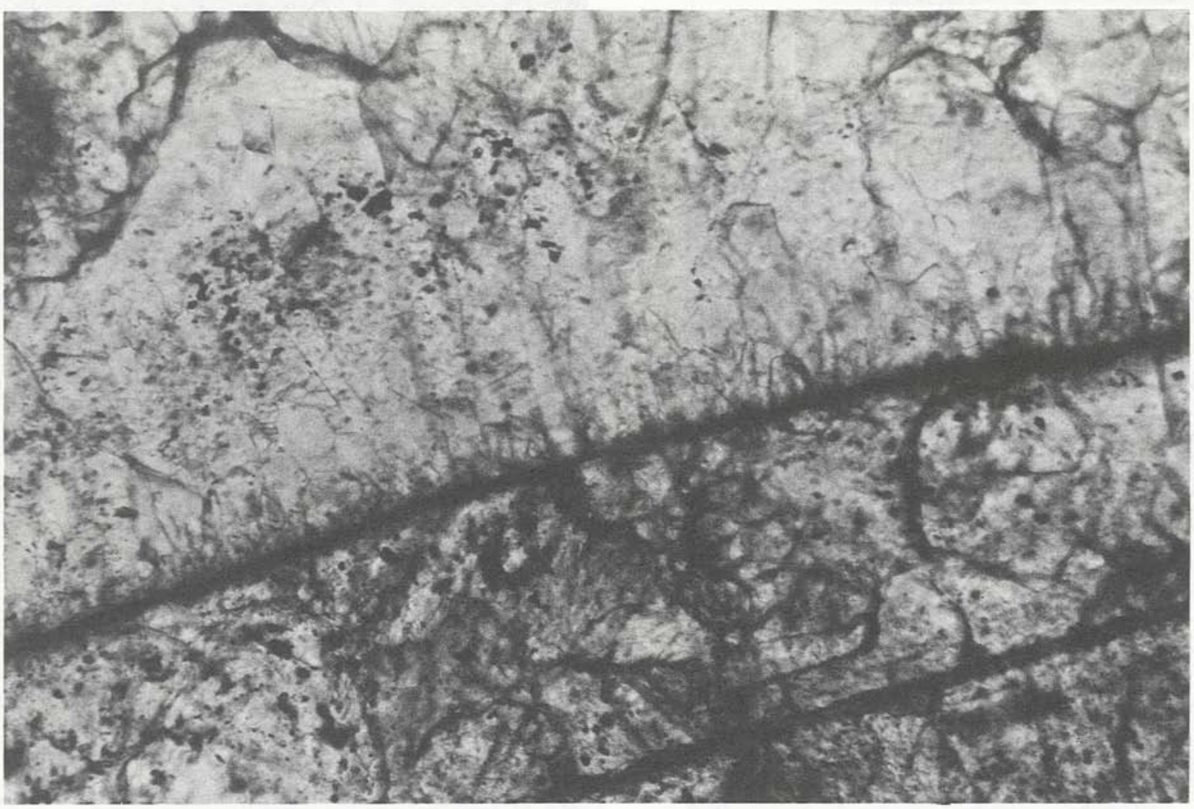


ALAMO LUMBER 13,362 a.

CORE SLAB X1

ALAMO LUMBER 13,362 b.

THIN SECTION X40



ALAMO LUMBER 13,362 c.

THIN SECTION X125

Figure 12. Mollusk-miliolid grainstone. a. Even, parallel laminations and upward-fining graded units. b, c. Neomorphosed mollusk shell fragment with some original shell structure still preserved. Cement types include a thin crust of isopachous cement (P.BC) and more recent equant calcite (P.E).

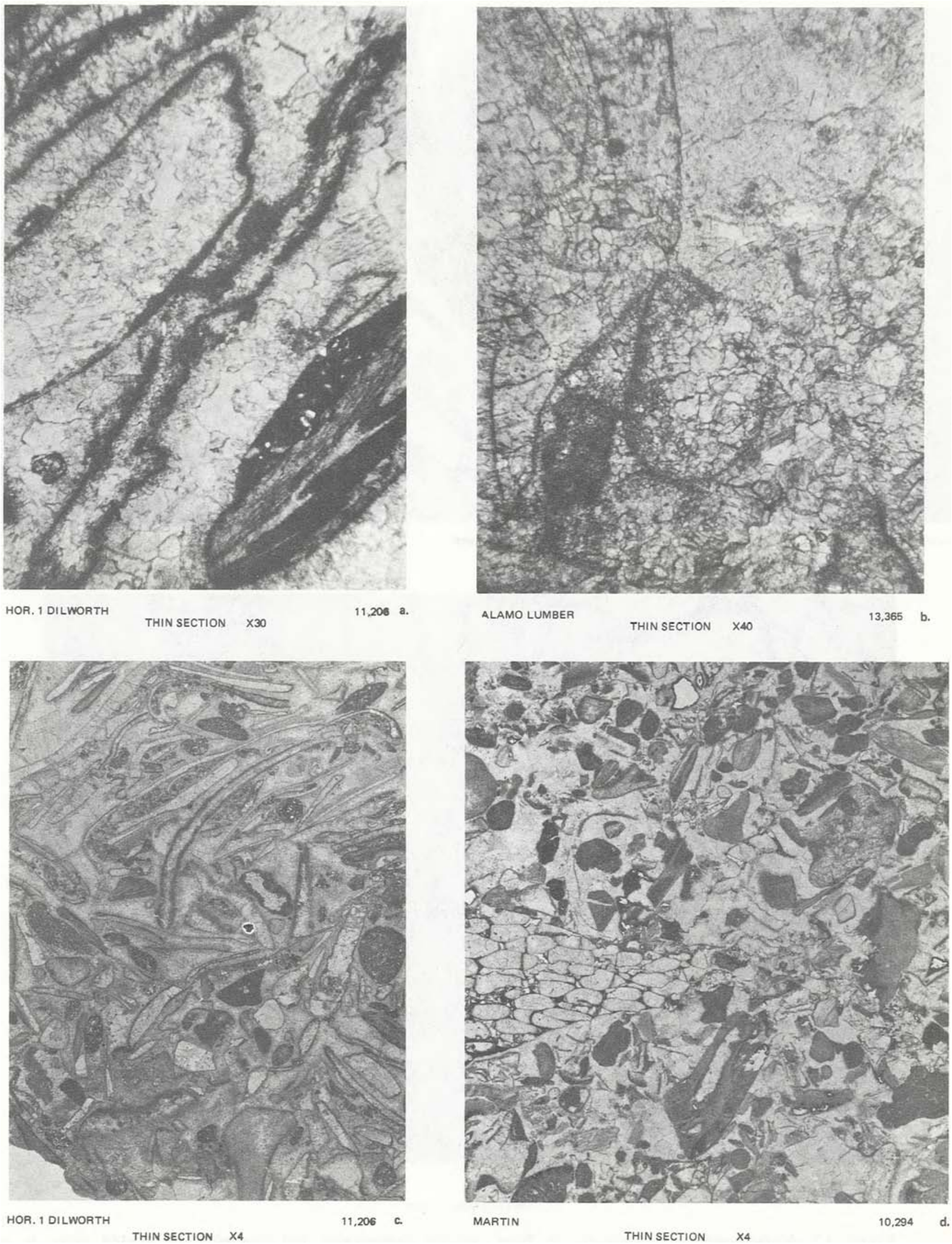


Figure 13. Mollusk-miliolid grainstone. a-d. Mollusk fragments have been either neomorphosed to equant calcite or completely leached, and the open space filled with equant calcite. Only the micrite rim around the original shell is left.

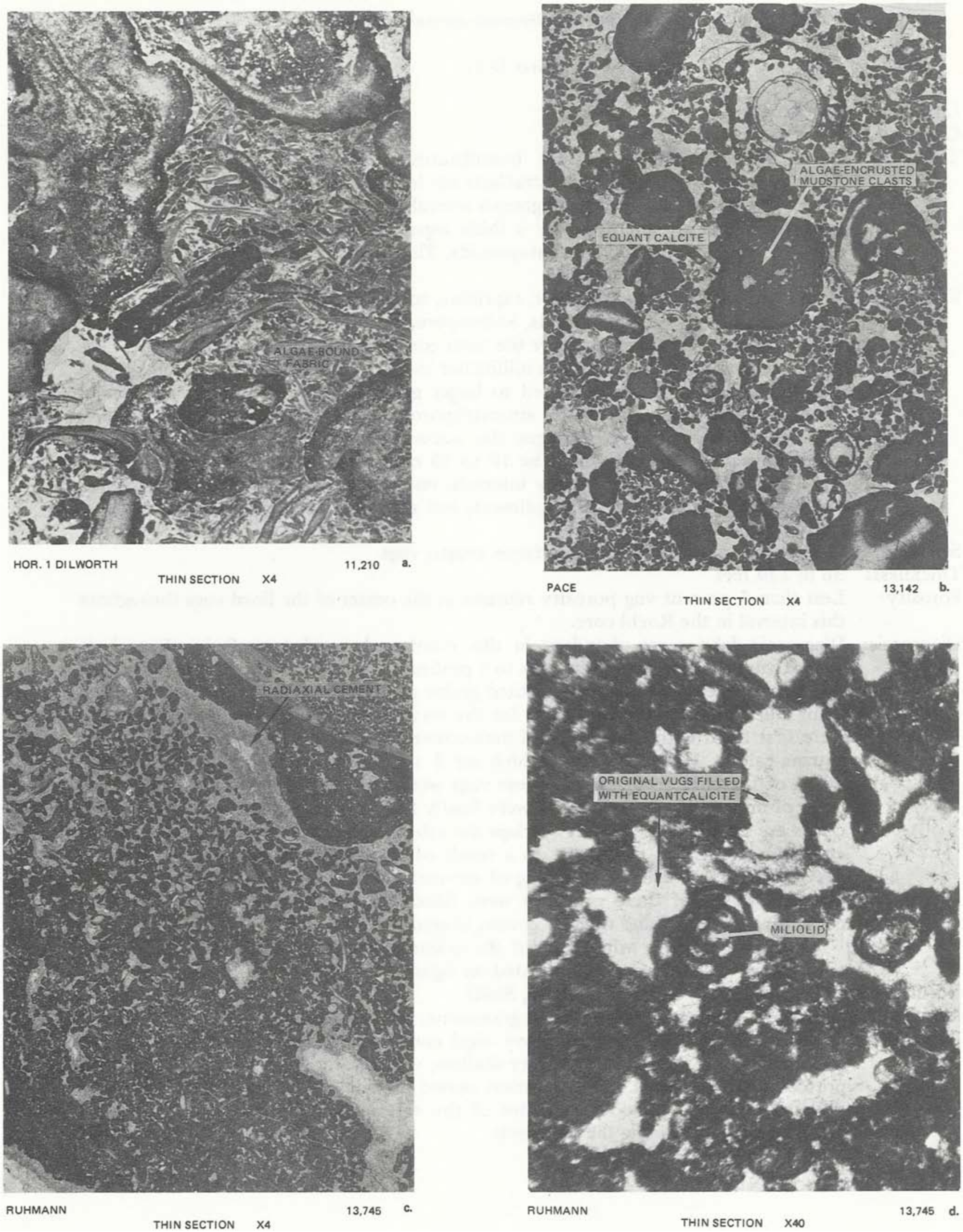


Figure 14. Mollusk-miliolid grainstone. a. Algae-bound fabric. b. Loosely packed bimodal grainstone. Large grains are algae-encrusted mudstone; fine grains consist of foraminifers and skeletal fragments. Intergranular spaces are filled with equant calcite. c. Grainstone with loose packing just under the vug lined with radiaxial cement. Packing is tighter away from the vug. d. Algae-bound fabric with vugs filled by equant calcite.

Algae-encrusted miliolid-coral-caprinid packstone

Figures 15-17

Lithology: Limestone
Color: Light to medium brown
Texture: Dominantly packstone, locally boundstone, grainstone, wackestone. Skeletal material is most common, but intraclasts are locally significant. Sorting is poor and ranges from very fine sand to fragments several centimeters in diameter. Most of the large fragments are encrusted by a thick algae-micrite coating; exceptions include some requienid shells and stromatoporoids. The finer material is coated thinly, if at all. The miliolids are not coated.
Fossils: Dominant—miliolids, *Dictyoconus*, caprinids, corals, encrusting algae
Also present—toucasids, radiolitids, *Solenopora*, stromatoporoids

Encrusting blue-green algae are the most common constituents of this facies. The algae occur as coatings less than a millimeter to a centimeter thick on skeletal grains. The thicker coatings are restricted to larger grains. In some cases the coatings of algae alternate with layers of stromatoporoid, with very gradational contacts between the two. Blue-green algae also occur as individual, discrete heads which when viewed in entirety would be 10 to 15 cm across and more than 20 cm high (figs. 15c, 16d). Finally, in many intervals, encrusting algal filaments are abundant and intimately mixed with the sediment, and thus must have provided a very stable substrate.

Structures: Geopetal structures, burrows, birdseye, crusts, vugs
Thickness: 36 to 179 feet
Porosity: Less than 5 percent vug porosity remains in the center of the lined vugs throughout this interval in the Roehl core.
Diagenesis: Diagenetic fabrics are abundant in this dominantly packstone facies. Irregularly shaped vugs from a few millimeters to a centimeter across are common as a result of the keystone effect of early-cemented grains protecting open spaces beneath from being filled with sediment. Except for the very center of the larger ones, these vugs were first filled with a thick rim of dark-colored, bladed calcite and then with clear, equant calcite. Horizontal vugs which are 5 to 6 mm wide and extend across the width of the core occur rarely. These vugs were lined top and bottom with a thick layer of impure, bladed crust, and were finally filled with clear, equant calcite. Some crusts are broken and one part overlaps the other, suggesting either movement of the crust by storms, or overthrust as a result of crystallization pressure. Other vugs developed as the result of leaching of stromatoporoid (fig. 16c) or requienid shell material. Some of these openings were filled very early by fine carbonate mud containing ostracods and then by coarse, bladed cement.

Displacive cement, which forced the grains apart by crystallization pressures is common in this facies and is illustrated on figure 17.

Occurrence: HOR 2 Dilworth, Roehl, Ruhmann, Smith
Associated Facies: Mollusk wackestone, rudist grainstone, miliolid wackestone
Depositional environment: Shelf margin. Heavy algal encrustations indicate that the affected sediment lay on the sea floor in very shallow, warm water (1 to 5 feet deep) in areas protected from normal water agitation caused by tidal exchange and wind-induced waves. The strong bimodal character of the sorting suggests that storms played a significant role in mixing the sediments.

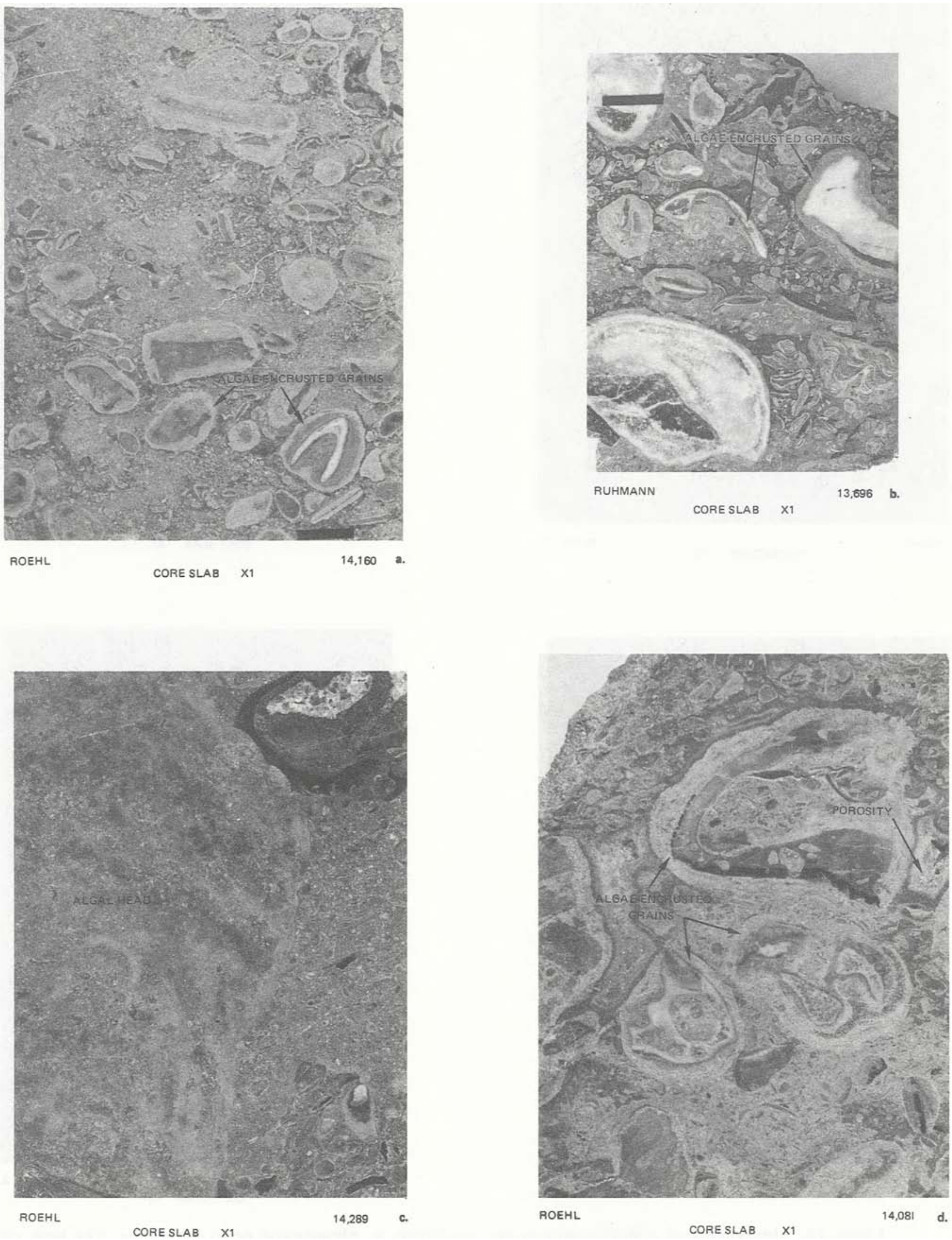


Figure 15. Algae-encrusted miliolid-coral-caprinid packstone. a. Algae-encrusted grains floating in a matrix of finer, uncoated grains and carbonate mud. b. Large irregular-shaped vugs, now filled with dark-colored calcite cement, were protected by the overlying, loosely packed algae-encrusted grains. c. Large algal head, on the left, with a requienid attached near the top. d. Large algae-encrusted shell fragments (requienids and caprinids) and associated large calcite-filled vugs.

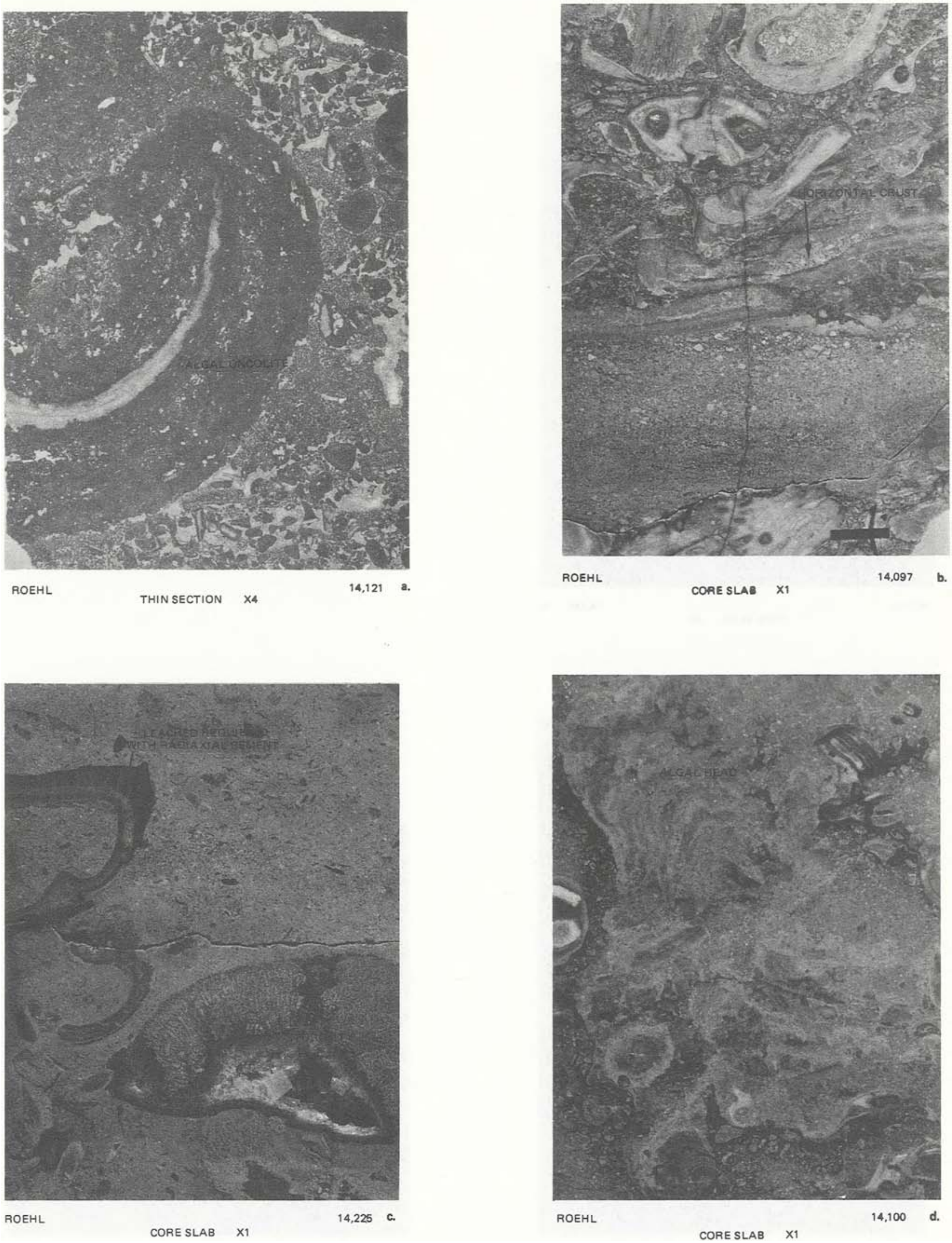


Figure 16. Algae-encrusted miliolid-coral-caprinid packstone. a. Algae-bound pellet grainstone. The large algal oncolite, with a mollusk shell as a nucleus, has been turned over from its original living position. b. A horizontal vug now lined with radiaxial and equant cements which has broken and now overlaps. This type of structure has been interpreted as resulting from the crystallization pressure within a carbonate crust. c. Vugs which originated from the leaching of a requienid shell and of the center of a stromatoporoid. These vugs are filled with a thick layer of radiaxial cement and equant calcite. A large opening still remains in the stromatoporoids. d. Large irregularly shaped vugs, now filled with dark-colored calcite, which were preserved around the edges and within the algal head.

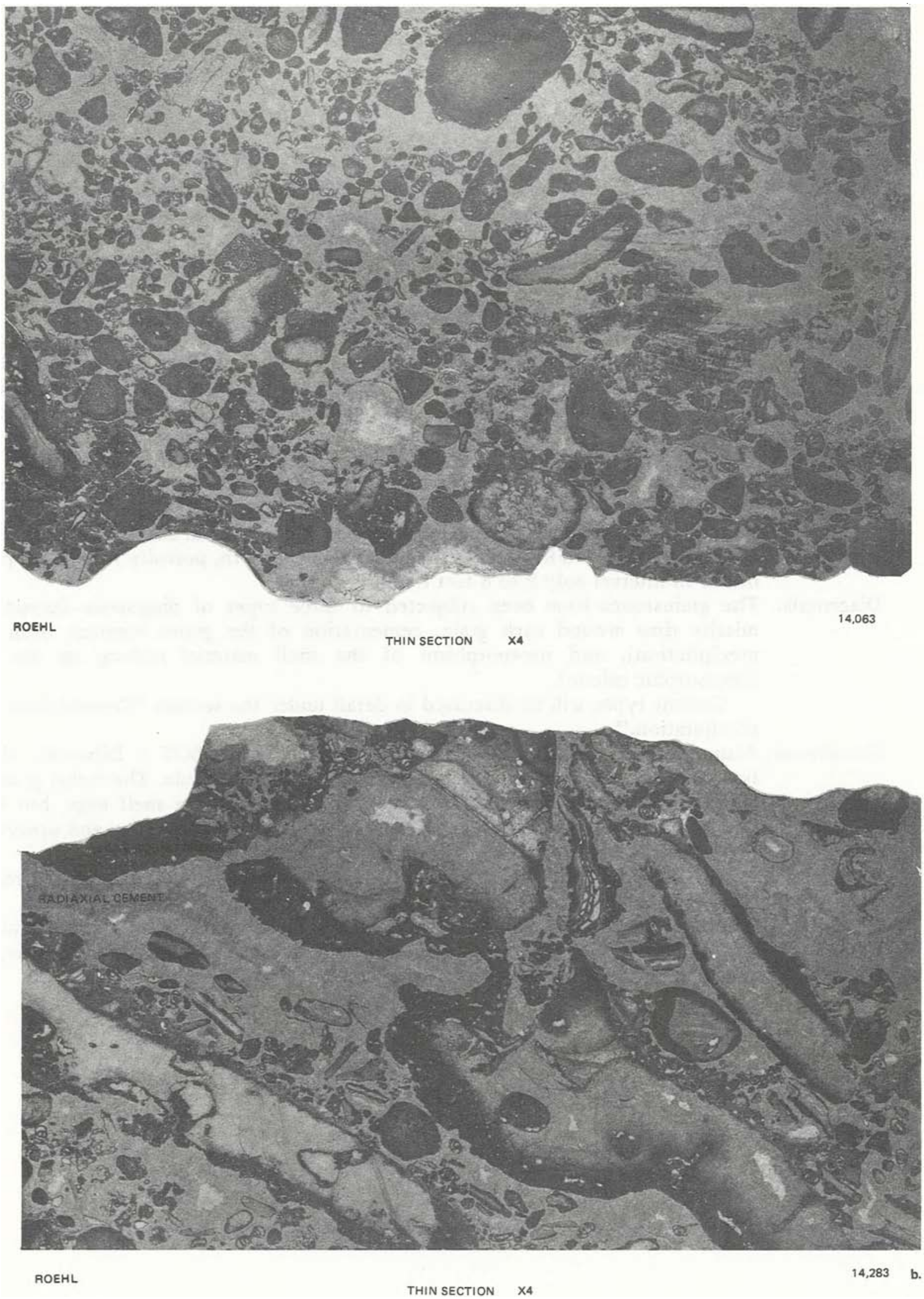


Figure 17. Algae-encrusted miliolid-coral-caprinid packstone. a. Very loose packing of intraclasts and skeletal grains, probably the result of displacive calcite precipitation of radiaxial cement. b. Algae-bound crusts protecting large horizontal vugs in which radiaxial cement was precipitated.

Rudist grainstone

Figures 18-20

Lithology: Limestone

Color: Medium to light brown

Texture: Dominantly grainstone, locally packstone. The grains are primarily skeletal but up to 20 percent are intraclasts. Grain size ranges from very fine sand to pebbles; sorting is commonly poor, but moderately sorted sands are present.

Fossils: Dominant—caprinids, corals, stromatoporoids, *Dictyoconus*, encrusting algae, mollusks

Also present—echinoids, requienids, miliolids, radiolitids, *Solenopora*

Structures: Parallel horizontal laminae, cross laminae, graded beds (both fining upward and coarsening upward), and vertical fractures. The vertical alternation of units, distinct because of differences in grain size, sorting, grading, and bedding types, is clearly illustrated by the sequence within the grainstone body of the Alamo Lumber (fig. 19).

Thickness: 7 to 122 feet. Commonly the grain bodies are between 20 and 60 feet thick.

Porosity: Less than 5 percent primary intraparticle porosity is sporadically scattered throughout this facies in the Alamo Lumber, Martin, and Schulz cores. Less than 5 percent moldic and primary interparticle porosity occurs in the Kahanek and HOR 2 Dilworth; in the HOR 1 Dilworth and HOR 2 Dilworth, porosity reaches 10 percent but in an interval only 2 to 8 feet thick.

Diagenesis: The grainstones have been subjected to three types of diagenesis—formation of micrite rims around each grain, cementation of the grains (cement from direct precipitation), and neomorphism of the shell material making up the grains (neomorphic calcite).

Cement types will be discussed in detail under the section "Cement from direct precipitation."

Occurrence: Alamo Lumber, HOR 1 Dilworth, HOR 2 Dilworth, SOT 1 Dilworth, Horton, Isaacks, Kahanek, Martin, Peschel, Roehl, Ruhmann, Schulz. The rudist grainstone facies forms a very narrow, discontinuous band along the shelf edge, but is best developed downsection in wells located just landward of the edge and upsection in the seaward wells.

Associated facies: Caprinid-coral wackestone, requienid boundstone, algae-encrusted miliolid-coral-caprinid packstone, echinoid packstone, miliolid wackestone

Depositional environment: Shelf margin. Variations in laminations, bedding, grading, grain size, and sorting suggest that grain bodies accumulated as beaches, offshore bars, spits, and tidal channels in water depths ranging from 0 to 10 feet.

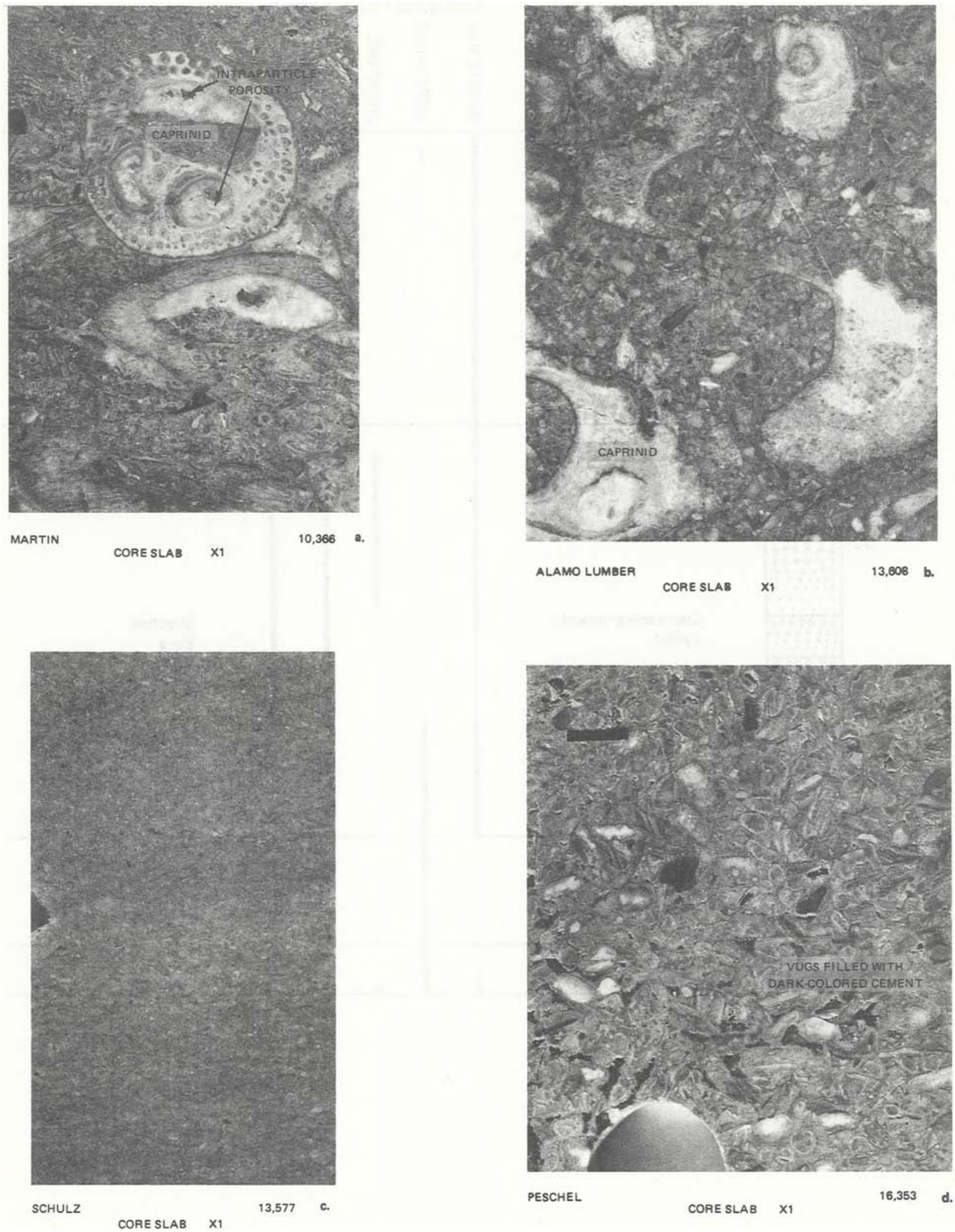


Figure 18. Rudist grainstone. a, b. Poorly sorted, bimodal grainstone. c. Very fine grainstone with irregular argillaceous laminae. d. Large, irregular intergranular spaces filled with dark-colored cement.

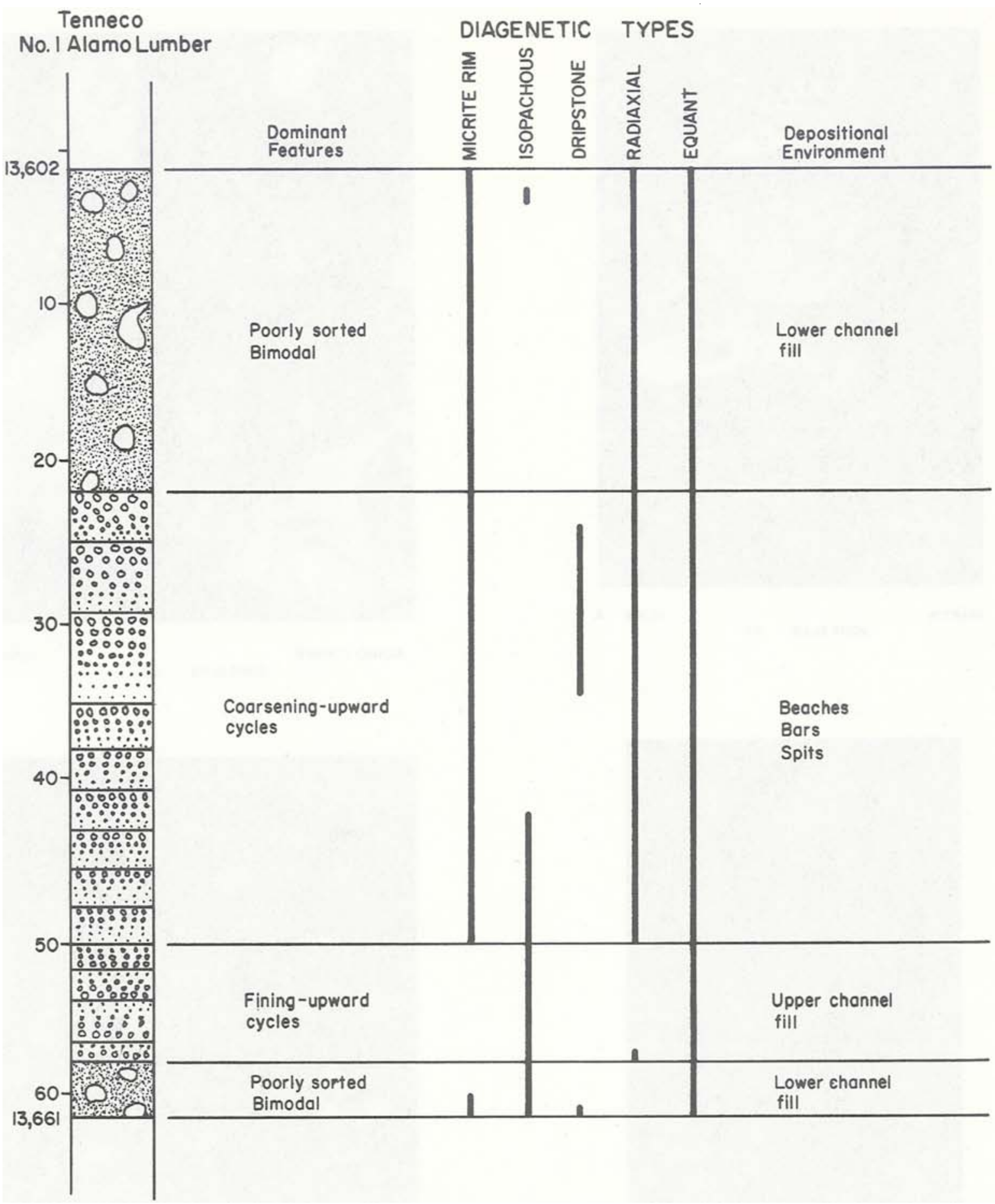


Figure 19. Vertical sequence of internal structures in a single grainstone body.

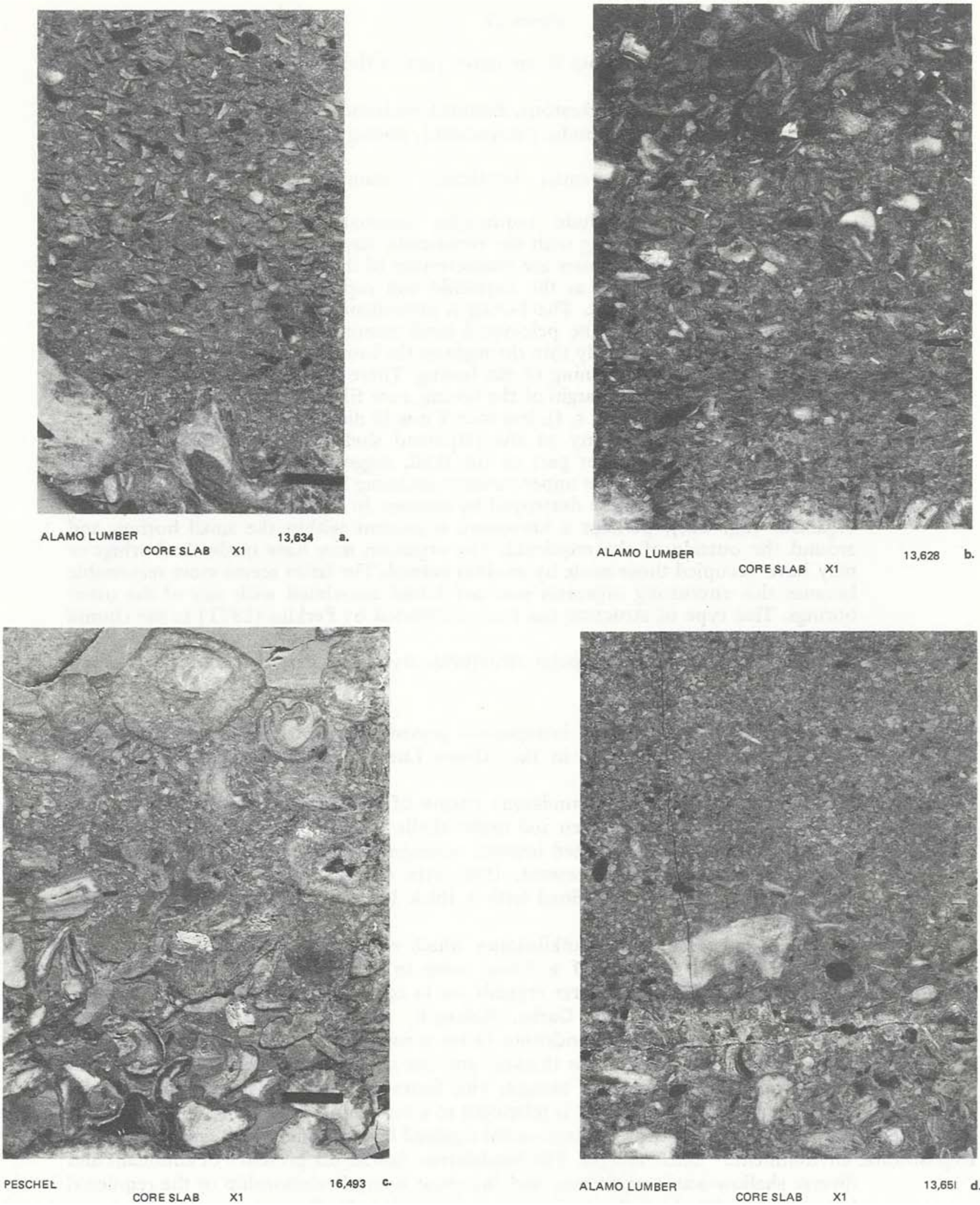


Figure 20. Rudist grainstone. a, b. Coarsening-upward cycles. c, d. Fining-upward cycles.

Requienid boundstone

Figure 21

Lithology: Limestone (locally argillaceous in the upper part of the facies in the O'Neal)
Color: Light to medium brown
Texture: Boundstone, packstone, wackestone. Boundstone is most common
Fossils: Dominant—requienids, caprinids, *Dictyoconus*, boring pelecypods, stromatoporoids, bryozoans, corals
Also present—echinoids, small benthonic foraminifers, mollusks, miliolids, *Solenopora*, encrusting algae

Binding organisms include requienids, stromatoporoids, encrusting algae, bryozoans, and corals. Along with the requienids, large boring pelecypods (fig. 21a, e) 5 mm to 2.5 cm in diameter are characteristic of this facies. These animals bored into any hard surface such as the requienid and caprinid shells, stromatoporoids, corals, or lithified sediment. The boring is pear-shaped in longitudinal section and circular in cross section. The pelecypod itself commonly is preserved within the boring. The shell is uniformly thin throughout the lower part but expands and flares out at the top near the opening of the boring. There is a thin space of 1 to 2 mm between the shell and the margin of the boring, now filled with sediment.

Smaller borings (fig. 21a, c, f), less than 1 mm in diameter and several millimeters long, are abundant in many of the requienid shells. In some, the borings are abundant only on the upper part of the shell, suggesting that the lower half was buried in sediment while the upper surface was being bored; in other requienids, the shells are almost completely destroyed by borings. In the Schulz core, an encrusting organism (fig. 21f), perhaps a bryozoan, is present within the small borings and around the outside of the requienid. The organism may have made the borings or may have occupied those made by another animal. The latter seems more reasonable because this encrusting organism was not found associated with any of the other borings. This type of structure has been attributed by Perkins (1971) to the clionid sponge.

Structures: Borings, small channels, geopetal structures, stylolites, irregular laminae, solution cavities
Thickness: 30 to 151 feet
Porosity: Less than 5 percent primary intraparticle porosity within the body cavities of the requienids occurs irregularly in the Alamo Lumber, Peschel, Schulz, Smith, and Tomasek cores.
Diagenesis: Because of the packstone-boundstone nature of this facies, many small, irregular voids were maintained between and under shells. These voids were later filled by a variety of cements and silt-sized internal sediment. Many voids were first lined with a layer of isopachous rim cement, then with coarse mosaic cement or internal sediment. Others were first lined with a thick layer of radiaxial cement and then filled with coarse mosaic.

Zoned, euhedral quartz poikilotopes which replace matrix and fossils make up approximately 30 percent of a 2-foot zone in the Schulz (13,692-13,694 feet). About 70 percent of the quartz crystals are in optical continuity with one another.

Occurrence: Alamo Lumber, Chapman, Garbe, Kahanek, Martin, O'Neal, Peschel, Schulz, Tomasek. The requienid boundstone facies constitutes one of the more important facies of the shelf edge, and is thickest and occurs highest in the section in wells on the seaward edge of the shelf margin. This facies thins rapidly and occurs deeper in the section shelfward. Thus, it is restricted to a very thin band.
Associated facies: Caprinid-coral wackestone, coral-caprinid boundstone, rudist grainstone
Depositional environment: Shelf margin. The boundstone fabric, the presence of abundant and diverse shallow-water organisms, and the close vertical relationship of the requienid boundstone with the rudist grainstone, suggest that this facies accumulated in water depths of 5 to 15 feet as discontinuous reefs or banks.

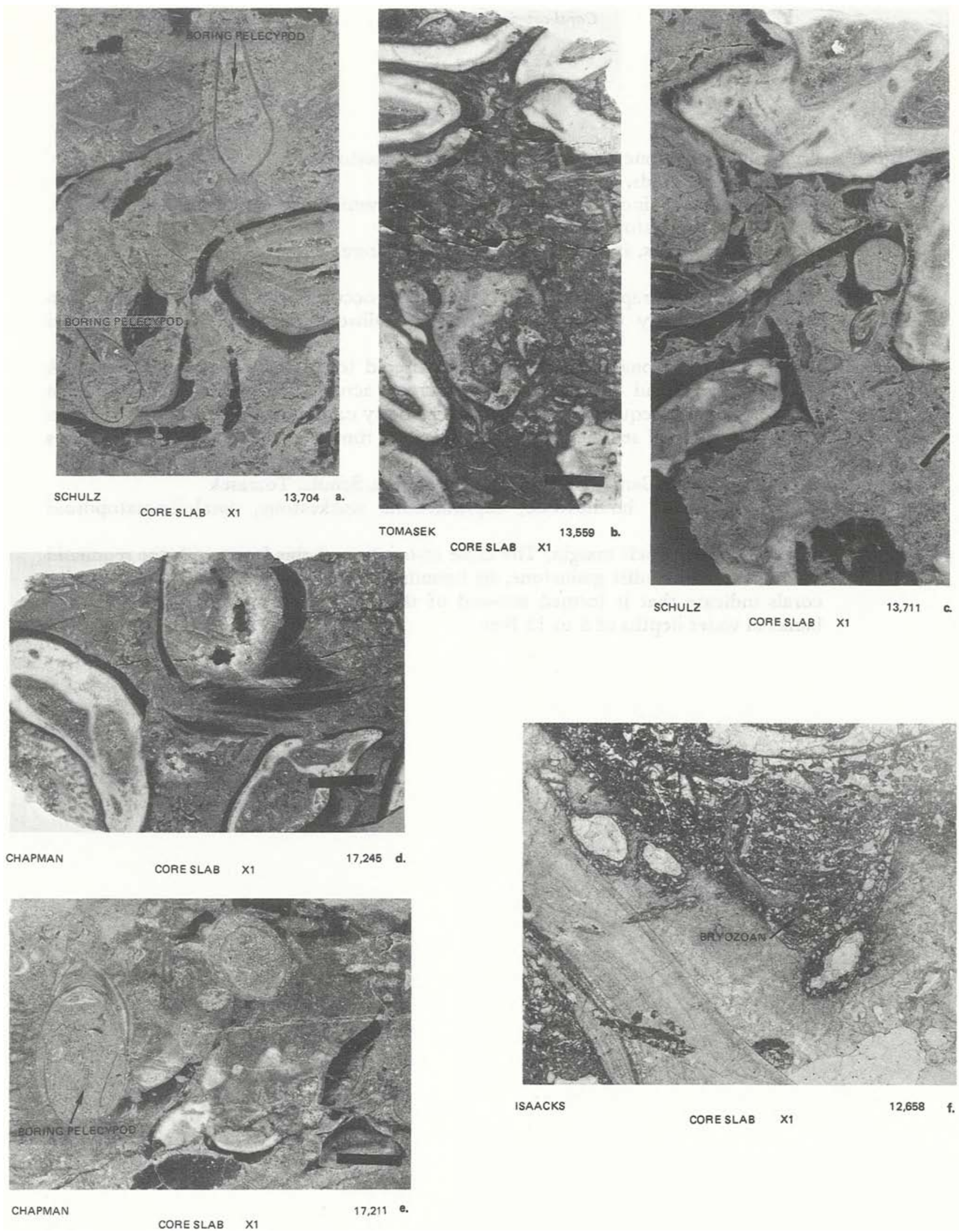


Figure 21. Requienid boundstone. a-e. The requienid shells (black outer shell and white inner layer) are attached to one another or to stromatoporoids or corals. Boring pelecypods, which truncate parts of requienids, are present in (a) and (e). f. Encrusting bryozoan binding the sediment around a requienid shell and lining the sides of borings within the shell.

Coral-caprinid boundstone

Figure 22

Lithology: Limestone
Color: Cream
Texture: Primarily boundstone, some packstone and wackestone
Fossils: Dominant—caprinids, corals
Also present—echinoids, small benthonic foraminifers, mollusks, *Dictyoconus*, *Solenopora*, stromatoporoids, boring pelecypods
Structures: Geopetal structures, stylolites, solution cavities (rare)
Thickness: 13 to 64 feet
Porosity: Sparse primary intraparticle porosity (fig. 22b) occurs in the Schulz core, and up to 5 percent porosity occurs in the HOR 1 Dilworth as small solution-enlarged intraparticle.
Diagenesis: Most of the carbonate matrix has been altered to microspar; particles average 4 microns across and some reach 20 microns across. The shell walls have been neomorphosed to equant calcite (N.E). The body cavities of the caprinids have been filled with internal sediment and calcite cement rims, often with several alternations (fig. 22d).
Occurrence: HOR 1 Dilworth, Garbe, Horton, Isaacks, Martin, Schulz, Tomasek
Associated facies: Requienid boundstone, caprinid-coral wackestone, coral-stromatoporoid boundstone
Depositional environment: Shelf margin. The close association of this facies with the requienid boundstone and rudist grainstone, its boundstone fabric, and abundance of massive corals indicate that it formed seaward of the rudist grainstone as patch reefs and banks in water depths of 5 to 15 feet.

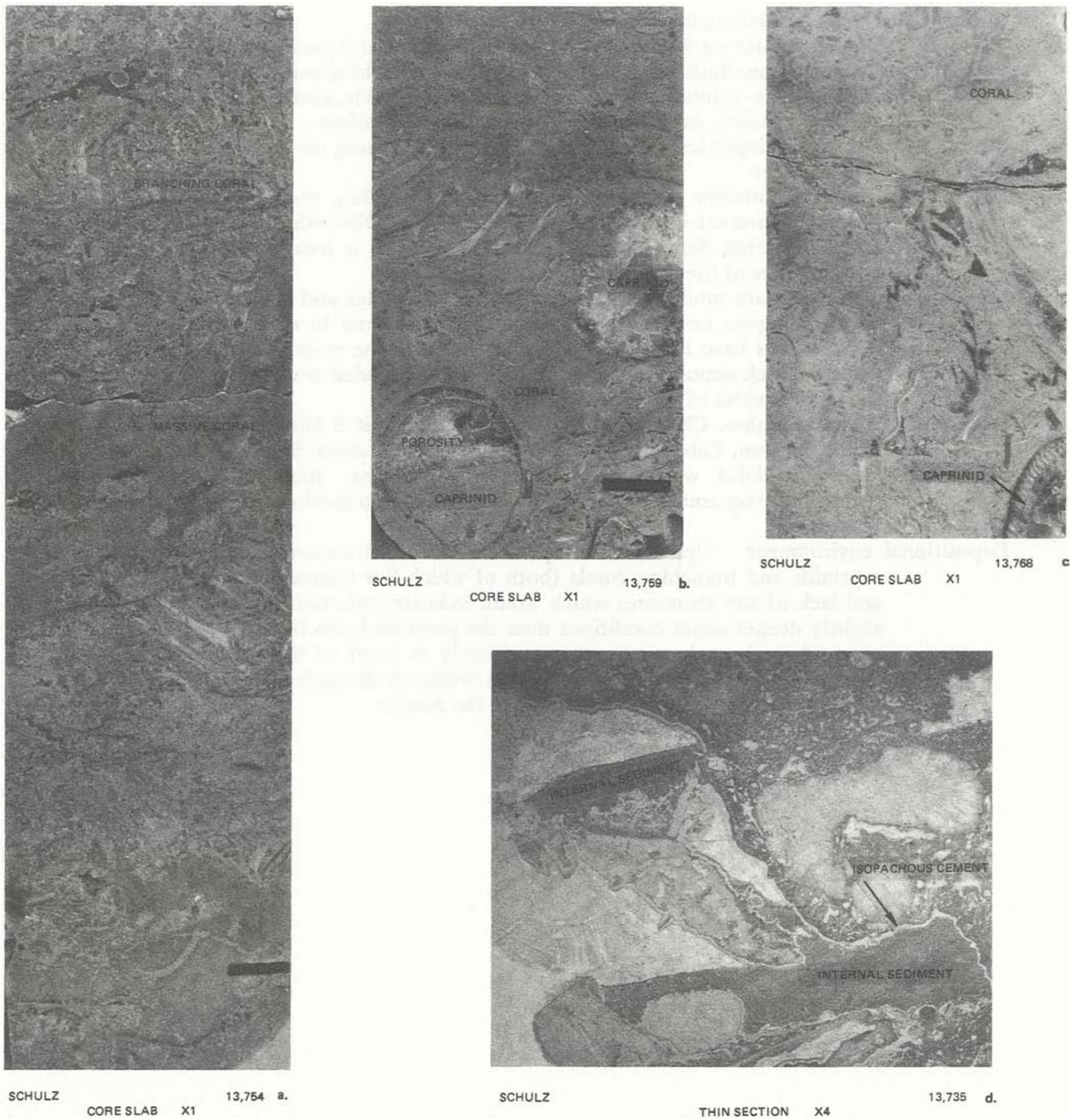


Figure 22. Coral-caprinid boundstone. a. Boundstone composed of branching and massive corals. b. Caprinids, now largely leached, bound together by massive coral. c. Boundstone of caprinids (right) and massive coral (top and left). d. Large vug within a coral boundstone. The vug was first lined with a thin isopachous cement, then partially filled with internal sediment, lined again with isopachous and radiaxial cement, and finally filled with equant calcite.

Caprinid-coral wackestone

Figure 23

Lithology: Limestone
Color: Cream to medium brown
Texture: Predominantly wackestone with some boundstone and packstone
Fossils: Dominant—mollusks, *Dictyoconus*, caprinids, branching corals
Also present—echinoids, *Solenopora*, stromatoporoids, sponges, dasycladacean algae, requienid rudists, miliolids, small benthonic foraminifers
Structures: Poorly developed irregular laminae, geopetal structures, rare burrows, stylolites
Thickness: 7 to 158 feet
Porosity: Scattered primary intraparticle porosity (fig. 23a), probably not exceeding 5 percent, is present in thin intervals in the HOR 1 Dilworth, SOT 1 Dilworth, Garbe, Horton, Martin, Schulz, and Smith. This porosity is located primarily within the body cavities of the caprinids.
Diagenesis: The carbonate mud occurs as micrite-sized particles and as microspar. Most shells have undergone neomorphism from original material to equant calcite (N.E) (fig. 23d); others have been completely leached and the voids filled with calcite crusts (P.BC). Thick deposits of internal sediment and bladed crust cement are common in the body cavities of the caprinids (fig. 23d).
Occurrence: Alamo Lumber, Chapman, HOR 1 Dilworth, HOR 2 Dilworth, SOT 1 Dilworth, Garbe, Horton, Kahanek, Martin, O'Neal, Peschel, Schulz, Smith, Tomasek
Associated facies: Miliolid wackestone, mollusk wackestone, mollusk grainstone, rudist grainstone, requienid boundstone, coral-caprinid boundstone, coral-stromatoporoid boundstone
Depositional environment: Upper shelf slope. Abundance of carbonate mud, dominance of caprinids and branching corals (both of which live unattached on a mud bottom), and lack of any structures which would indicate sustained currents, are evidence of slightly deeper water conditions than the previous facies from the shelf margin. The caprinid-coral wackestone occurs primarily in front of the shelf margin in water depths of 10 to 30 feet; it also occurs in breaks or channels between the shelf-margin facies and along a thin band just behind the margin.

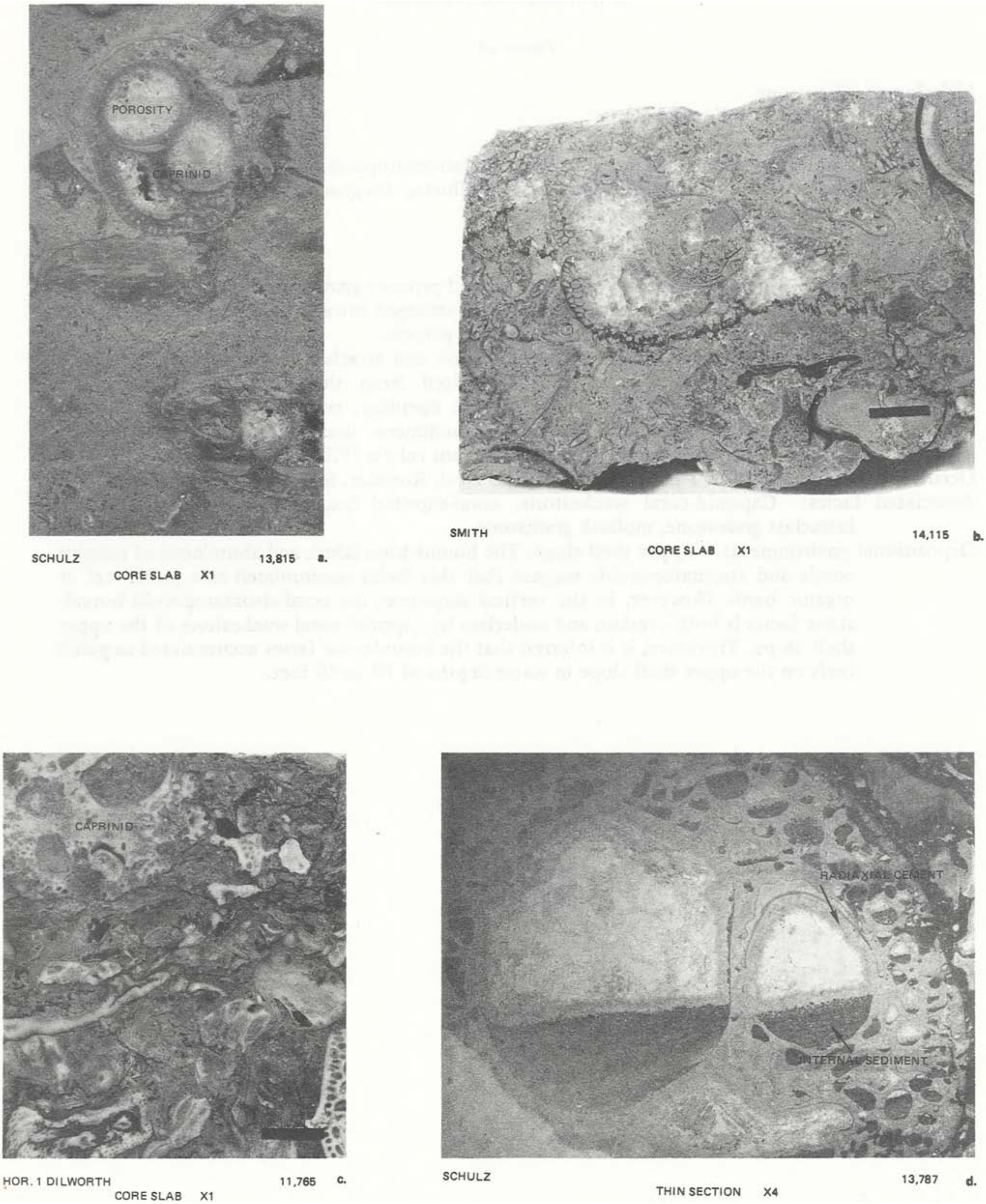


Figure 23. Caprinid-coral wackestone. a-c. Large, whole caprinids in a carbonate mud matrix. d. Caprinid shell with the lower part of the body cavity, tooth cavities, and canals filled with internal sediment. After this was deposited in the shell, the remaining openings were lined with a thick layer of radiaxial cement and finally filled with equant calcite.

Coral-stromatoporoid boundstone

Figure 24

Lithology: Limestone
Color: Cream to medium brown
Texture: Boundstone
Fossils: Dominant—branching and massive corals, stromatoporoids
Also present—echinoids, ostracods, mollusks, *Dictyoconus*, caprinids, toucasids, encrusting algae, *Solenopora*, sponges
Structures: Geopetal
Thickness: 6 to 190 feet
Porosity: Up to 3 percent internal sediment-reduced primary growth-framework porosity (fig. 24a). In the Tomasek very fine solution-enlarged intraparticle porosity reaches 10 percent and in the Horton and Roessler, 5 percent.
Diagenesis: The larger organisms are in growth position and attached to one another, forming a bound fabric. Many open spaces resulted from the sheltering effect of the intergrown organisms (fig. 24a, e). These openings, commonly irregular in shape, were partially filled with fine internal sediment, lined with coarse bladed crust cement (P.BC), and finally filled with equant calcite (P.E).
Occurrence: Chapman, HOR 1 Dilworth, Horton, O'Neal, Roessler, Schulz, Smith, Tomasek
Associated facies: Caprinid-coral wackestone, coral-caprinid boundstone, rudist grainstone, intraclast grainstone, mollusk grainstone
Depositional environment: Upper shelf slope. The boundstone fabric and abundance of massive corals and stromatoporoids suggest that this facies accumulated as a patch reef or organic bank. However, in the vertical sequence, the coral-stromatoporoid boundstone facies is both overlain and underlain by caprinid-coral wackestone of the upper shelf slope. Therefore, it is inferred that the boundstone facies accumulated as patch reefs on the upper shelf slope in water depths of 10 to 30 feet.

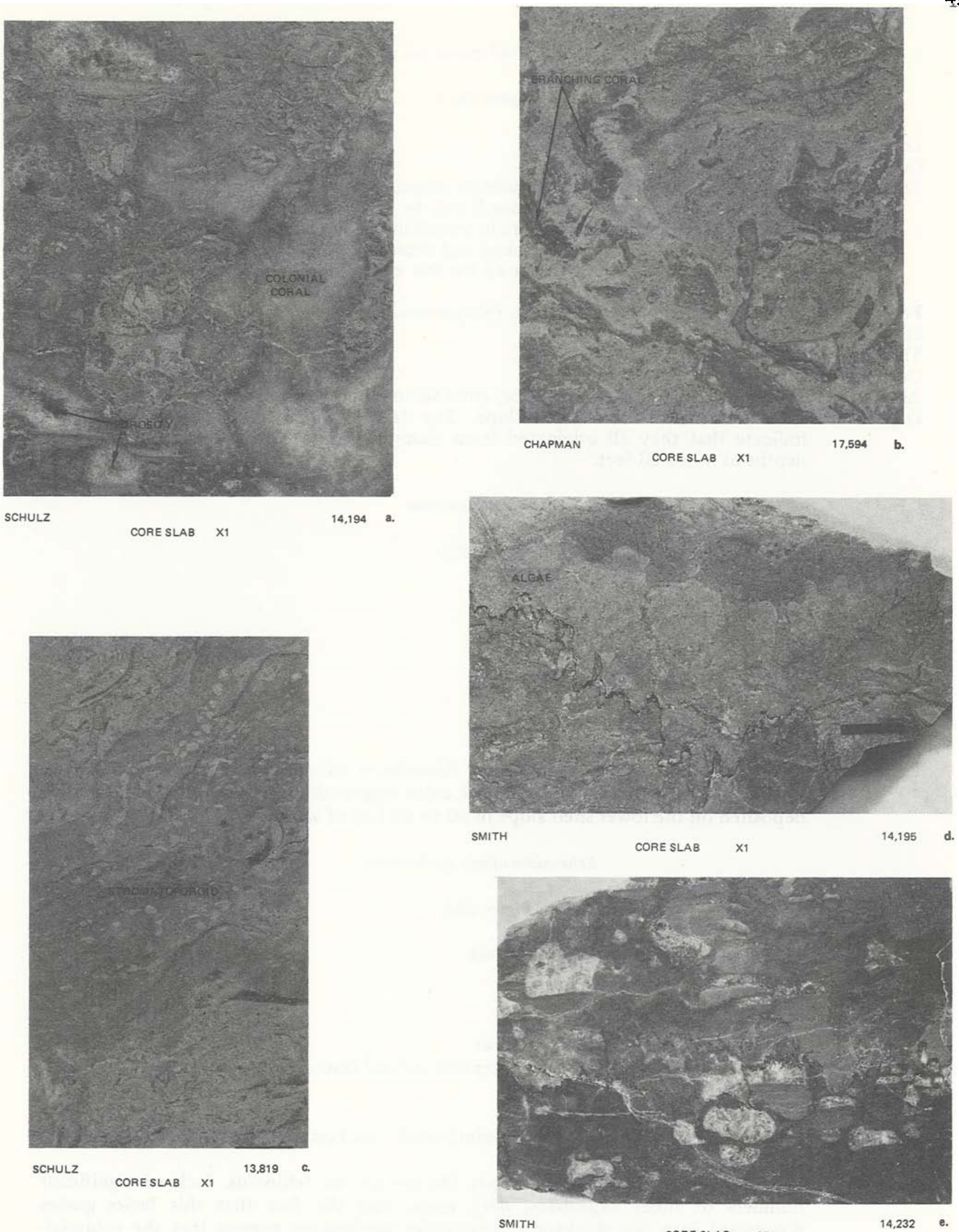


Figure 24. Coral-stromatoporoid boundstone. a. Boundstone of massive colonial coral. Vugs between corals have internal sediment. b. Branching corals and stromatoporoids forming a bound fabric. c. Laminar stromatoporoid. The vug formed under the stromatoporoid was later filled with internal sediment and equant calcite. d. Zone of laterally linked hemispheroidal algae. e. Abundant vugs developed within a stromatoporoid boundstone. The vugs were later filled with internal sediment and equant calcite.

Intraclast grainstone

Figure 25a, b

Lithology: Limestone
Color: Light to dark brown
Texture: Grainstone. The grains are irregular in shape, and grain size distribution is bimodal. The large clasts range in size from 5 mm to 3 cm across, and the small clasts from 0.5 mm to 1 mm. Large grains are in stylolitic contact with one another (fig. 25a, b). The small grains are loosely packed and cemented with equant calcite (P.E). Several carbonate textures are represented by the clasts—mudstone, echinoid wackestone, and pellet grainstone.
Fossils: Echinoid and mollusk fragments, *Dictyoconus*
Structures: Stylolites
Thickness: 42 feet
Occurrence: Chapman
Associated facies: Caprinid-coral wackestone, coral-stromatoporoid boundstone
Depositional environment: Lower shelf slope. The faunas and textures of the intraclasts indicate that they all originated from slumping on the lower shelf slope in water depths of 30 to 60 feet.

Echinoid packstone

Figure 25c

Lithology: Limestone
Color: Medium brown
Texture: Packstone
Fossils: Dominant—echinoids
Also present—mollusks, *Dictyoconus*
Thickness: 20 to 270 feet
Occurrence: HOR 1 Dilworth, Tomasek
Associated facies: Rudist grainstone
Depositional environment: Lower shelf slope. Abundance of echinoids, lack of significant numbers of other organisms, and dark color suggest that the echinoid packstone was deposited on the lower shelf slope in 30 to 60 feet of water.

Echinoid-mollusk wackestone

Figure 25d, e

Lithology: Limestone and argillaceous limestone
Color: Medium to dark brown
Texture: Wackestone
Fossils: Dominant—echinoids, mollusks
Also present—miliolids, *Dictyoconus*
Structures: Irregular laminae common, stylolites and vertical fractures rare
Thickness: 322 to 405 feet
Occurrence: Chapman, Tomasek
Associated facies: Mollusk grainstone, caprinid-coral wackestone, argillaceous planktonic foraminifer wackestone
Depositional environment: Lower shelf slope. Occurrence of echinoids, lack of significant numbers of other organisms, dark color, and the fact that this facies grades downward into the planktonic foraminifer wackestone suggest that the echinoid-mollusk wackestone was deposited on the lower shelf slope in 30 to 60 feet of water.

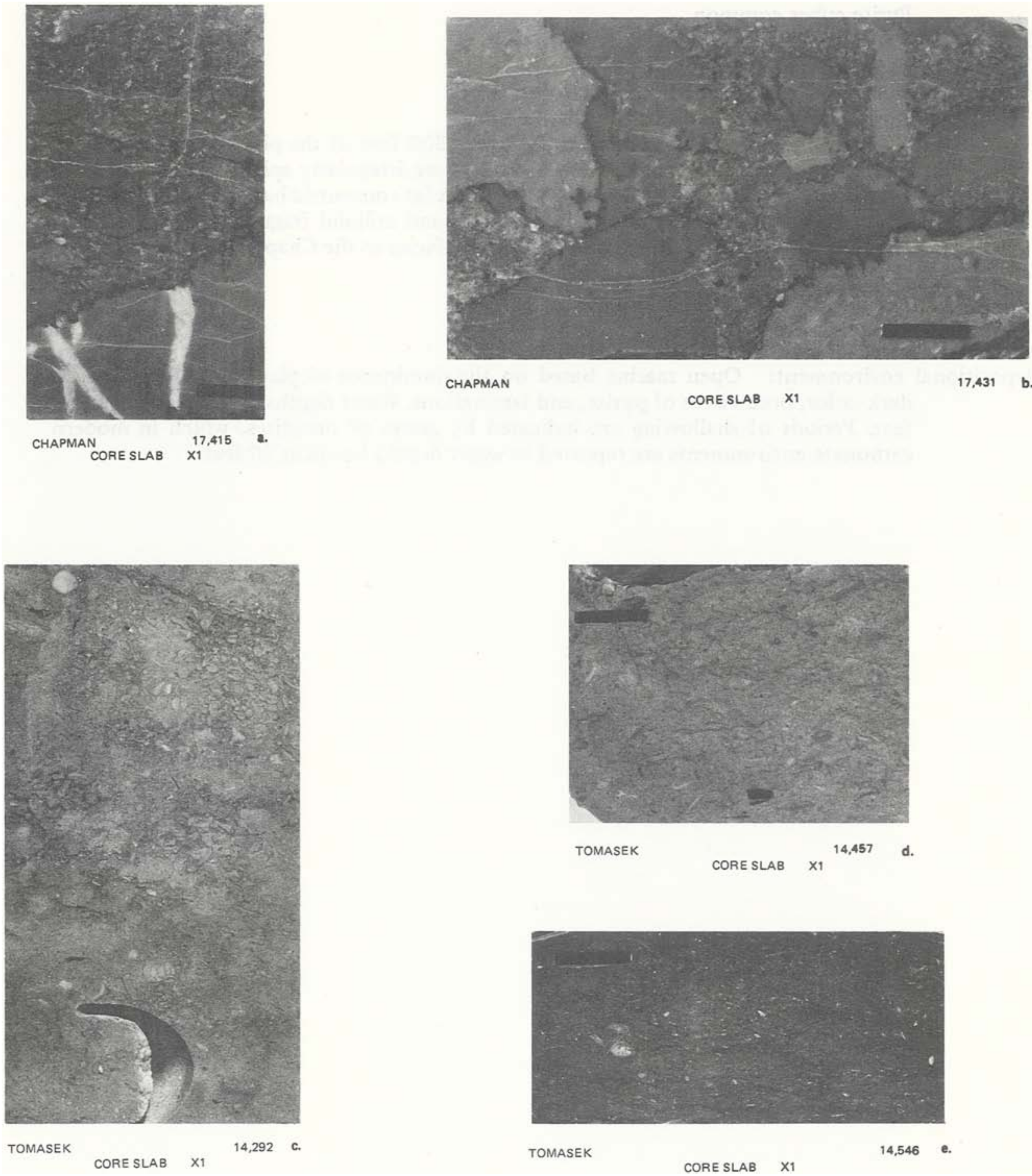


Figure 25. a, b. Intraclast grainstone. The intraclasts vary in composition from pellet grainstone to echinoid wackestone and mudstone. Most grains are in stylolitic contact. c. Echinoid packstone. d, e. Echinoid-mollusk wackestone.

Planktonic foraminifer wackestone

Figure 26

Lithology: Argillaceous limestone
Pyrite cubes common
Color: Dark gray to dark brown
Texture: Mudstone to wackestone
Fossils: Dominant—planktonic foraminifers, ostracods
Also present—echinoids, thin-shelled mollusks

Algal oncolites are common in the lower 300 feet of the planktonic foraminifer wackestone in the Tomasek. These oncolites are irregularly spherical and vary from 1 to 5 mm in diameter. They consist of irregular concentric bands of probable algal origin, with incorporated mollusk, echinoid, and miliolid fragments. Thin zones of oncolites also occur in the central part of this facies in the Chapman well.

Structures: Horizontal irregular laminae, small burrows
Thickness: 650 to 730 feet
Occurrence: Chapman, Tomasek
Associated facies: Echinoid-mollusk wackestone
Depositional environment: Open marine based on the dominance of planktonic foraminifers, dark color, occurrence of pyrite, and laminations. Water depths were greater than 60 feet. Periods of shallowing are indicated by zones of oncolites, which in modern carbonate environments are reported in water depths less than 20 feet.

ISAACKS 12,439 a.
CORE SLAB X1

ROEHL 13,963 b.
CORE SLAB X1

TOMASEK 15,161 c.
CORE SLAB X1

HOR. 1 DILWORTH 11,152 d.
THIN SECTION X50

Figure 26. Planktonic foraminifer wackestone. a, b. Dark-colored mudstone with vague laminations. c, d. Wackestone with abundant planktonic foraminifers and rare echinoid spines and mollusk fragments.

Distribution of Facies

In most detailed subsurface studies the vertical control of facies distribution is more complete than the lateral. This is definitely the case for the Stuart City Trend because of the relatively few numbers of wells, resulting in poor lateral control; on the other hand, long continuous cores were taken from several of these wells giving us, at least locally, excellent vertical coverage. Several facies cross sections (one strike section and four dip sections) have been constructed in order to include all the wells studied (figs. 27-31). In this manner, the general facies types, the thickness and depth of each facies, and the relationships of the facies to one another are shown. On each section, the core information is shown with the dark pattern within the well bore. Interpretation between control points is necessary even for the most closely spaced wells; the interpretive portion is indicated by the lighter pattern.

The planktonic foraminifer wackestone makes up the lower half of the Stuart City Formation and grades upward in the middle part into various echinoid-mollusk facies (echinoid-mollusk wackestone, echinoid packstone, mollusk wackestone, and mollusk grainstone). Because few cores were taken from this portion of the section, the position of these lower shelf-slope facies is shown only on figure 6, which includes the deeper penetrating wells. The facies of the remaining upper part are shown on the facies cross sections. Note, particularly on the strike section (fig. 27), that the facies patterns are grouped into three units: the lower unit includes the caprinid-coral wackestone and coral-stromatoporoid boundstone facies; the middle unit includes the coral-caprinid boundstone, requienid boundstone, and rudist grainstone; and the upper unit includes the toucasid wackestone, mollusk wackestone, and miliolid wackestone facies.

Because this is a progradational cycle, the position and thickness of these units relative to one another on a strike section will vary depending on the position of the well with respect to the shelf edge: in other words, the farther landward from the shelf edge the well occurs, the lower in the section each of these contacts occurs. Consequently, detailed correlation of individual facies would be difficult and was not attempted on the strike section A-A′ (fig. 27). The upward, seaward migration of facies is readily seen on the dip sections (figs. 28-31). Even when control wells are projected from considerable distances, a consistent picture of progradation of facies emerges from each section.

Detailed correlation of facies from well to well between control points is based largely on the vertical relationships of those same facies in each well. Justification for these detailed correlations is given in more detail below in the explanation accompanying each cross section. The datum for the cross section is the top of the Stuart City Formation; this top was picked from induction-electrical logs and is probably subject to adjustment of several tens of feet. However, the amount of error in picking the top would not significantly alter the facies pattern of the section.

Dip section B-B′ (fig. 28).—Dip section B-B′ shows the facies relationships in McMullen County between the Dilworth wells (HOR 1 Dilworth, HOR 2 Dilworth, and SOT 1 Dilworth) and the Amerada Horton. Long cores were taken from the HOR 1 and HOR 2 Dilworth wells, both of which are located back from the shelf margin in the shelf lagoon. The SOT 1 Dilworth is located on the shelf margin but cored only the upper 96 feet of the Stuart City. The Amerada Horton, also located on the shelf margin, cored several hundred feet of the Stuart City and has been added to this section.

Because of the relatively poor core control in the shelf-margin facies along this section, little can be said about their distribution except that shelf-margin facies do occur and they occur in the same vertical sequence as will be described in detail with the dip sections C-C′ and D-D′. In the Horton well, upper shelf-slope facies—caprinid-coral wackestone and coral-stromatoporoid boundstone—occur in the lower part. The shelf-margin facies, coral-caprinid boundstone, rudist grainstone, and caprinid-coral wackestone, occur above the upper shelf slope. Two feet from the top of the Stuart City Formation a 1-foot-thick bed of dolomite was logged in the caprinid-coral wackestone facies. This is the only dolomite logged from any cores used in this study. Shelf-margin facies also occur in the SOT Dilworth but they are much thinner than those in the truly shelf-margin wells and do not occur in the same vertical order of succession. The shelf-margin facies in the SOT Dilworth comprise the rudist grainstone, caprinid-coral wackestone, coral-caprinid boundstone, and coral-stromatoporoid boundstone. The total thickness of this group of facies is only 118 feet, less than half the thickness which is normal for the shelf margin. Shelf-margin facies—requienid boundstone and coral-caprinid boundstone—are present in the HOR 1 and 2 Dilworth but are relatively thin and, because of the location of these wells back from the Stuart City shelf edge, are located deep in the section (650 to 700 feet from the top). The shelf-margin sediments here, although thinner than those higher in the section, prograded more rapidly seaward and, therefore, the facies patterns between the HOR 1 and 2 Dilworth are nearly horizontal. Upper shelf-slope facies—coral-stromatoporoid boundstone and caprinid-coral wackestone—are present in the lowest core from the HOR 2 Dilworth; upper shelf-slope facies in the HOR 1 Dilworth consist of caprinid-coral wackestone and rudist grainstone. The rudist grainstone is anomalous in this position but probably represents the development of an offshore bar or channel. The upper shelf slope is underlain by lower shelf-slope echinoid packstone in the HOR 1 Dilworth.

Shelf-lagoon sediments make up the greater part of the cores from the HOR 1 Dilworth (upper 600 feet) and the HOR 2 Dilworth (upper 750 feet). They consist of miliolid wackestone, caprinid-coral wackestone, mollusk-miliolid grainstone, mollusk wackestone, toucasid wackestone, and rudist grainstone. The mollusk-miliolid grainstone and miliolid wackestone contain abundant algal structures, particularly in the lower half of the section. Birdseye structures are common in both wells. A thick section of rudist grainstone occurs at the top of the cored interval, near the top of the Stuart City Limestone, in the HOR 2 Dilworth. This is a unique occurrence for this facies in the shelf lagoon and it cannot be readily explained. Perhaps it represents reef talus from a rudist patch reef located back on the shelf lagoon. Note that the correlation lines between the two Dilworth wells are essentially horizontal, indicating rather uniform conditions throughout the area. The upper contact of the shelf lagoon with the overlying planktonic foraminifer wackestone was cored in the HOR 1 Dilworth; the skeletal grains near the contact are highly altered, but no structures were observed that would indicate the presence of an exposure surface.

Dip section C-C′ (fig. 29).—This section illustrates the detailed facies changes which occur between two Tenneco wells—Alamo Lumber and Schulz—which are less than 1 mile apart. Keith (1963) described briefly but very well the facies which occur in these two wells, and showed the general relationship between them. Open-marine and lower shelf-slope rocks were not cored in either well. At 14,050 feet, based on questionable log correlations, the deeper penetrating Alamo Lumber well encountered what is probably the top of the lower shelf slope (top of Glen Rose?); this is approximately 360 feet below the bottom of the cored interval. A thick section of upper shelf-slope carbonate occurs in the lower part of the Schulz core (13,776 feet to TD 13,987 feet). Except for a very thin interval of coral-stromatoporoid boundstone, the upper shelf slope consists of light-colored caprinid-coral wackestone. The top of the upper shelf slope in the Alamo Lumber well should be about 50 feet below the base of the cored interval.

Shelf-margin carbonates are present in both wells. In the Alamo Lumber, they occur 300 feet below the top of the Stuart City Formation and consist of requienid boundstone overlain by rudist grainstone and, finally, caprinid-coral wackestone; in the Schulz well, a short distance away, the same facies occur just over 100 feet from the top of the formation. In the Schulz, from the bottom upward, the vertical sequence is coral-caprinid boundstone, requienid boundstone, caprinid-coral wackestone, rudist grainstone, and caprinid-coral wackestone. The close relationship of the requienid boundstone and rudist grainstone is shown in both cores. The boundstone facies occurs beneath and seaward of the grainstone facies. Because of this relationship a grainstone body was added between the two wells, laterally equivalent to the requienid facies of the Schulz well.

Shelf-lagoon facies, consisting of miliolid wackestone, toucasid wackestone, mollusk wackestone, and mollusk-miliolid grainstone, comprise most of the cored interval in the Alamo Lumber well (above 13,595 feet, 287 feet thick). Miliolid wackestone makes up the greater part of the section. In the Schulz well, these facies occur only in the upper 182 feet, are thinner, and are represented by a smaller proportion of miliolid wackestone and larger proportion of mollusk grainstone.

The contact between the shelf-lagoon sediments of the Stuart City Formation and the overlying planktonic foraminifer wackestone was cored in the Schulz well. The upper 18 to 20 feet of the Stuart City contains brecciated zones and solution cavities which were attributed by Keith (1963) to submarine erosion. Whether submarine or subaerial, this event must have been minor compared to the overall tendency toward subsidence and rapid transgression by the deeper, open-water facies.

Dip section D-D′ (fig. 30).—This dip section represents the facies changes across the shelf edge in the vicinity of Bee County. The section goes

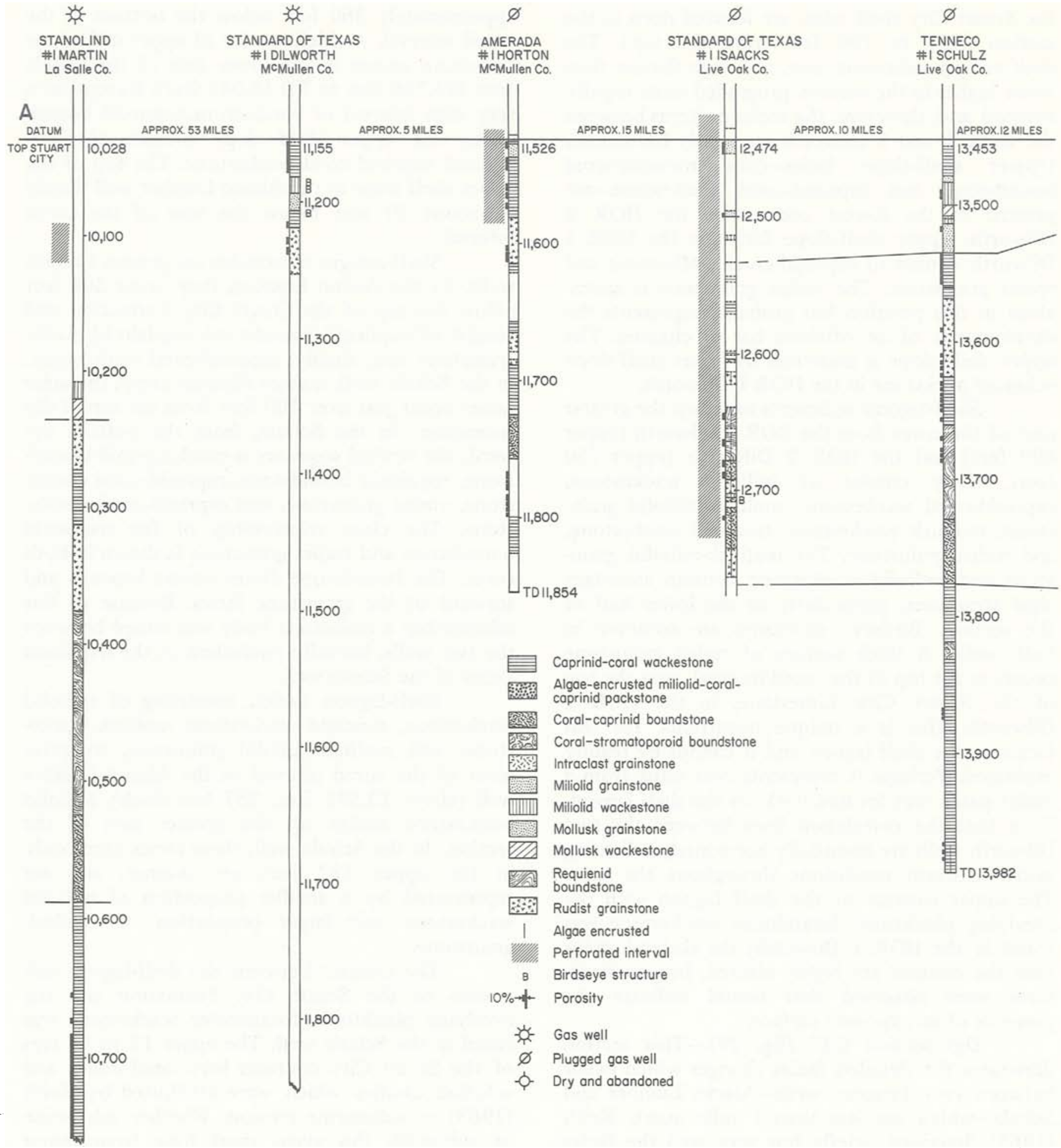
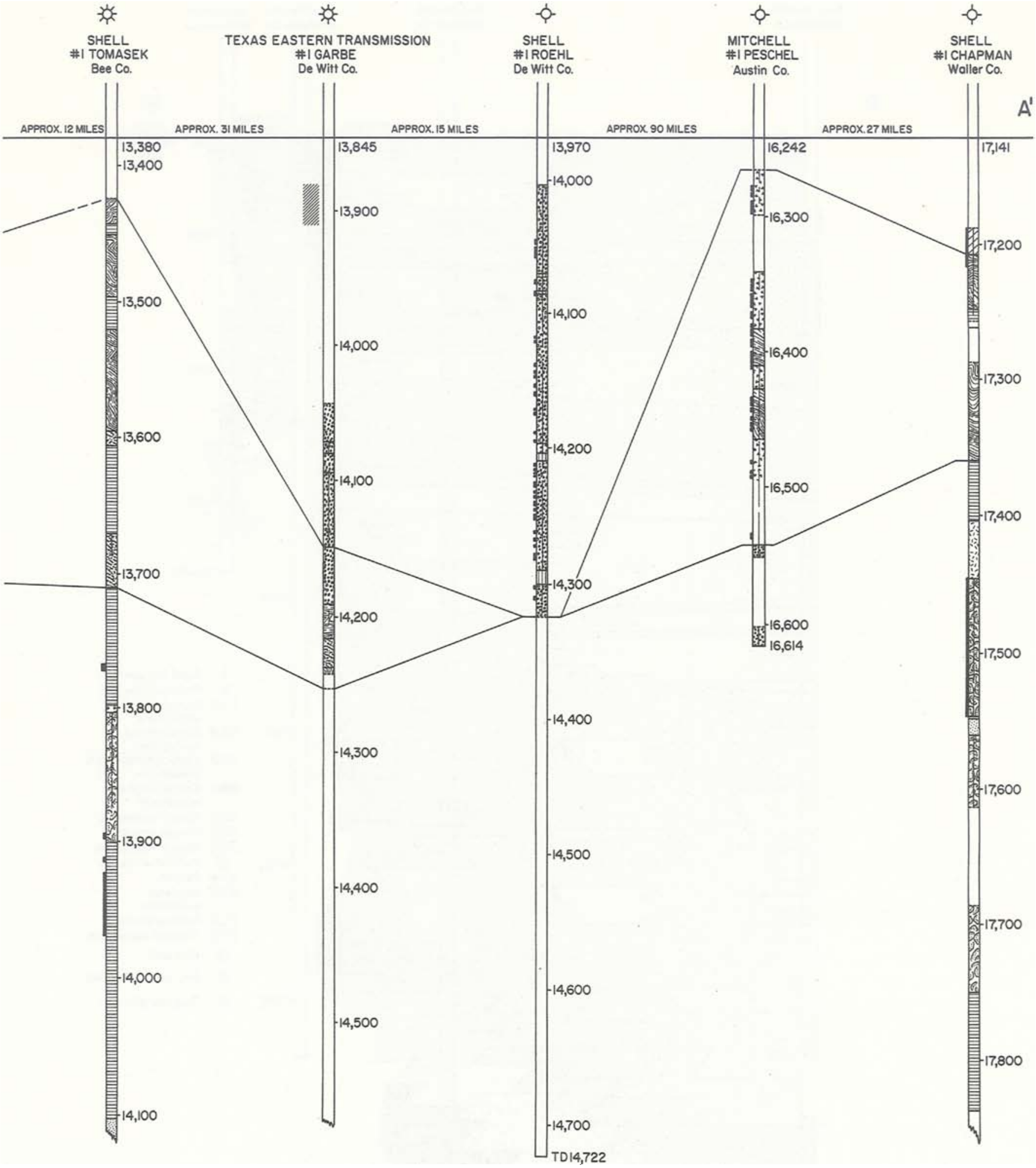


Figure 27. Facies cross section A-A′.


SHELL
#1 TOMASEK
Bee Co.
TEXAS EASTERN TRANSMISSION
#1 GARBE
De Witt Co.
SHELL
#1 ROEHL
De Witt Co.
MITCHELL
#1 PESCHEL
Austin Co.
SHELL
#1 CHAPMAN
Waller Co.
A'
APPROX. 12 MILES
APPROX. 31 MILES
APPROX. 15 MILES
APPROX. 90 MILES
APPROX. 27 MILES
13,380
13,400
13,500
13,600
13,700
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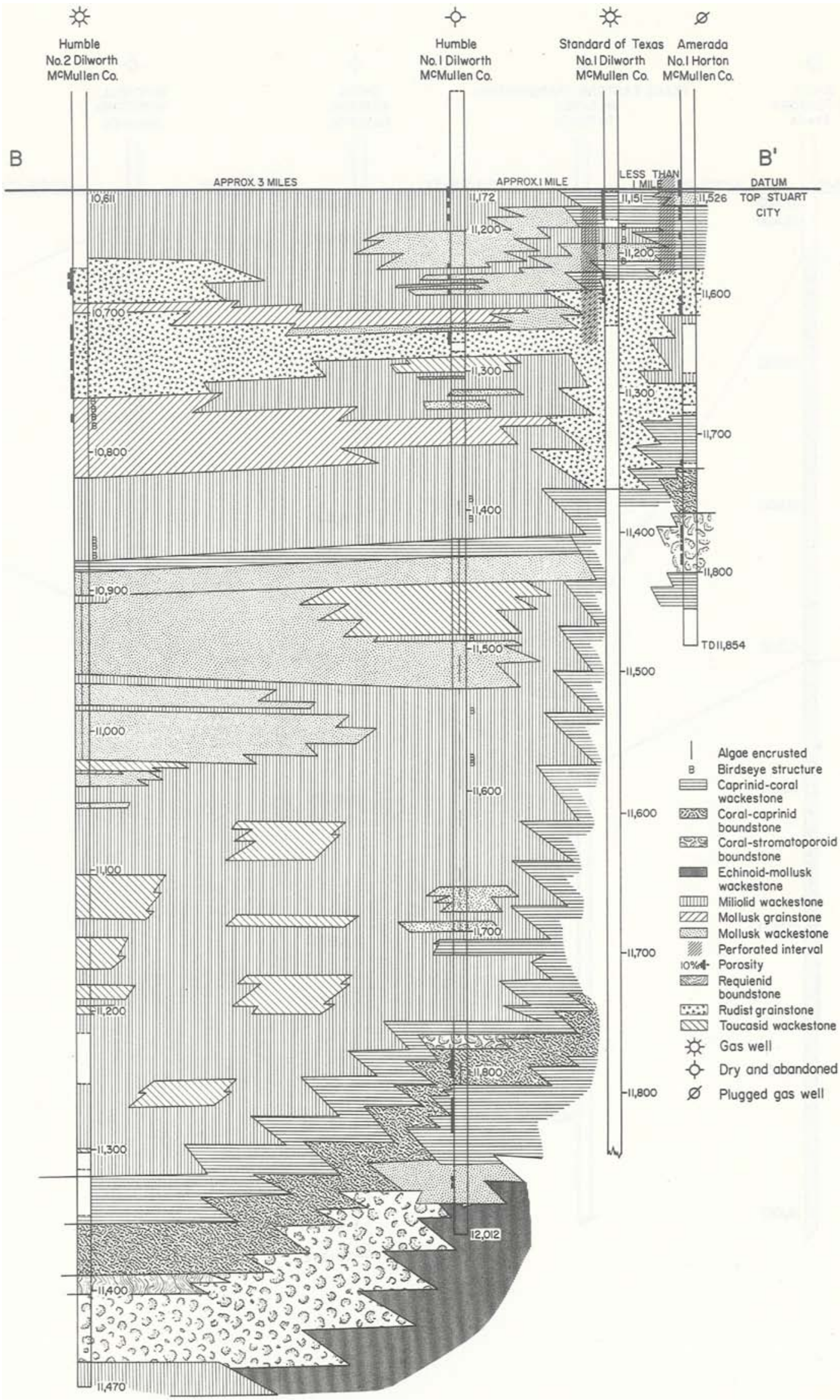


Figure 28. Facies cross section B-B′.

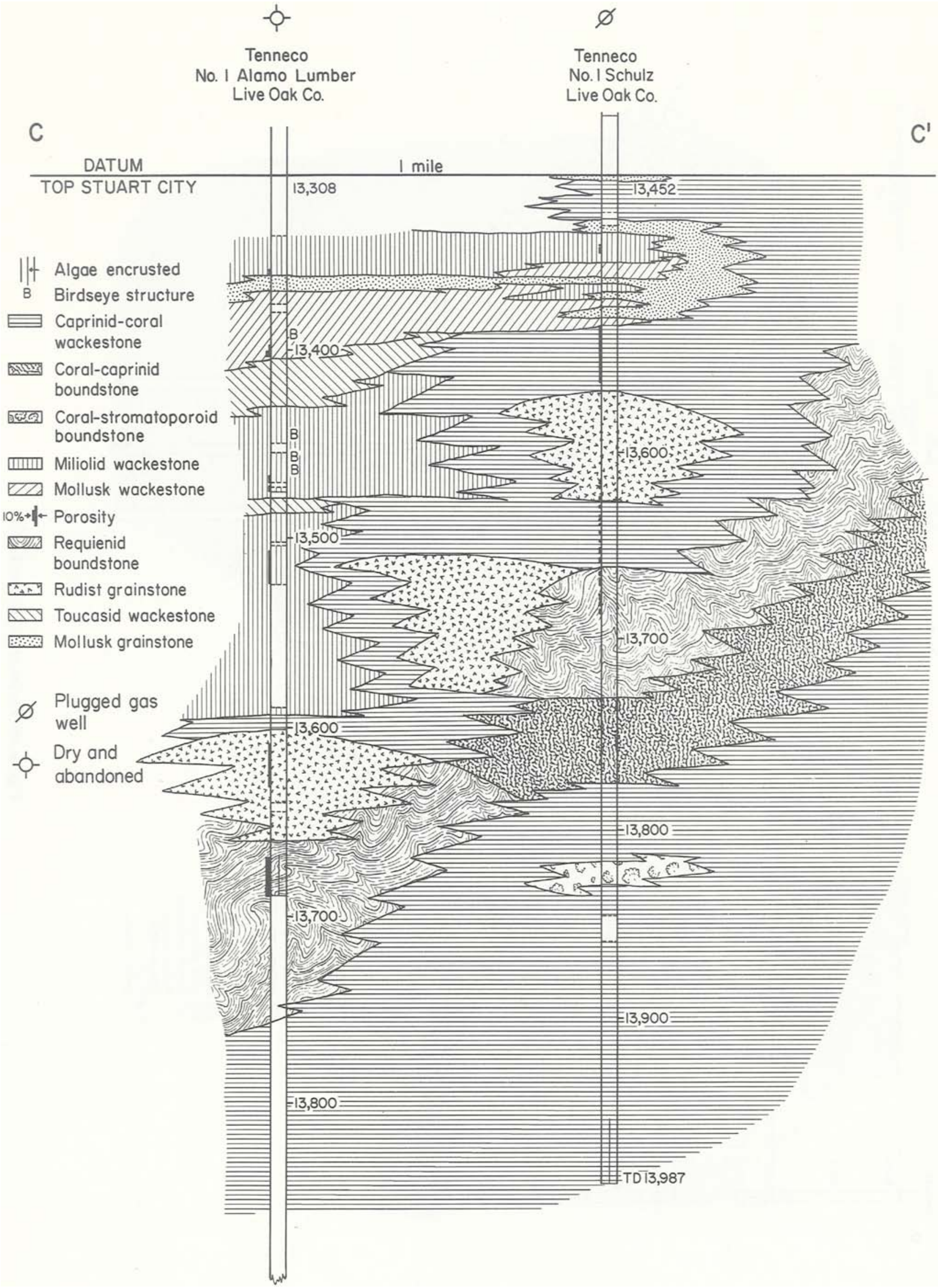


Figure 29. Facies cross section C-C′.

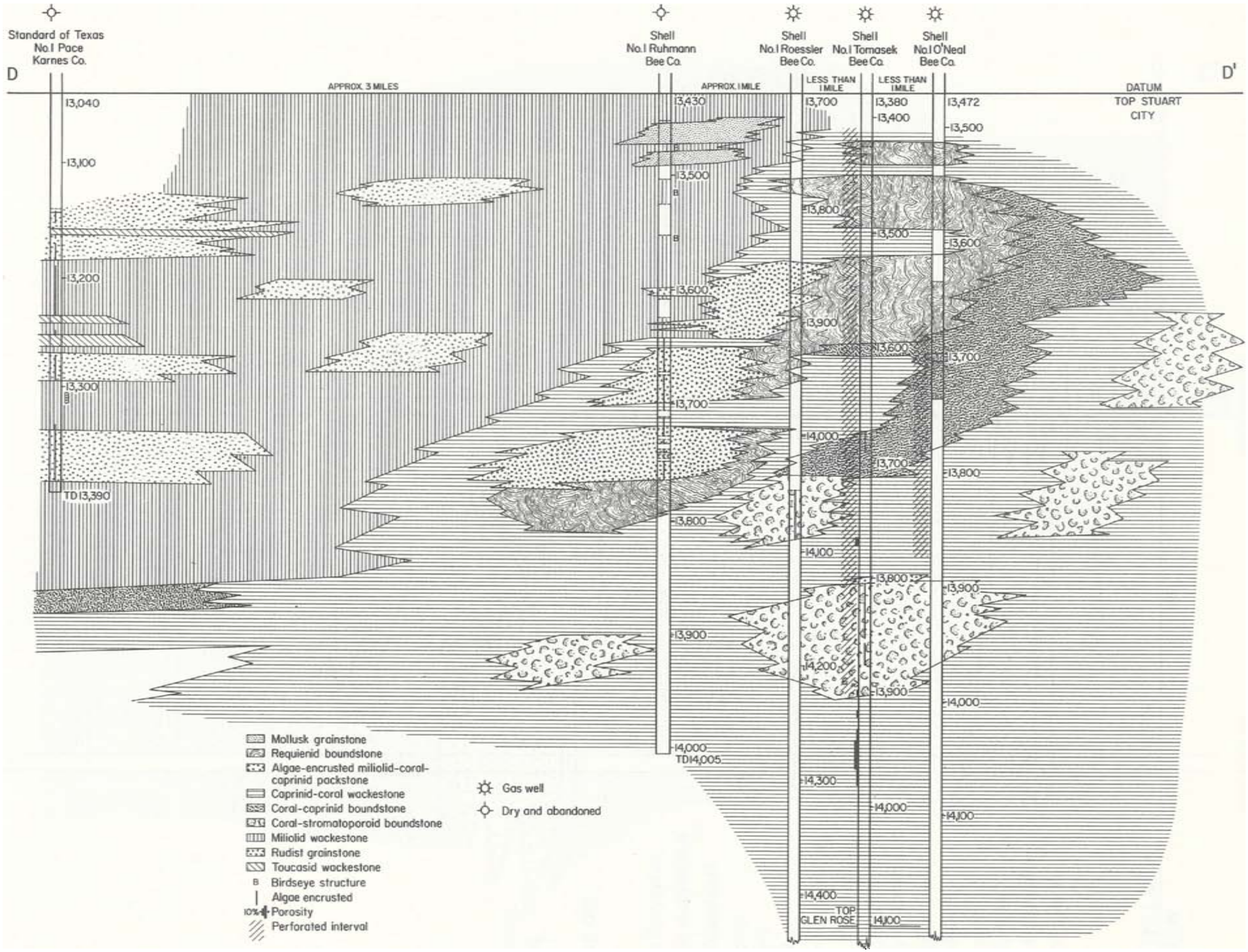


Figure 30. Facies cross section D-D′.

through the Shell Ruhmann; the Standard of Texas Pace has been projected into the section from the northeast in order to represent a shelfal well. The Shell wells, Roessler, Tomasek, and O'Neal, are spaced very close to one another, and have been projected in from the southwest to the line of section. The Ruhmann, Roessler, Tomasek, and O'Neal are considered to be shelf-margin wells. There is no core control basinward of the O'Neal.

Upper shelf-slope carbonates were cored only in the Tomasek well, where they make up the lower half of the cored interval below 13,710 feet. This interval is predominantly caprinid-coral wackestone, but a thick section of coral-caprinid boundstone also occurs. The upper contact of the caprinid-coral wackestone with the overlying shelf-margin carbonates should rise basinward toward the O'Neal well, is at about the same level in the nearby Roessler, and should be lower shelfward in the Ruhmann—below 13,850 feet. If the caprinid-coral facies extends landward as far as the Pace, it should occur several hundred feet lower than the total depth of the well.

The shelf-margin facies include the coral-caprinid boundstone, requienid boundstone, and rudist grainstone. On the basis of the vertical relationships of these facies in the Tenneco Alamo Lumber and Schulz wells (dip section C-C′, fig. 29), it is interpreted that requienid boundstone should occur below the lowest rudist grainstone in the Ruhmann; because fragments of requienids occur in this grainstone body and in the higher one, the requienid facies is interpreted to have occurred seaward of them also. The third, or highest, rudist grainstone body was added because of the occurrence of a thick requienid boundstone unit in the Tomasek between 13,519 and 13,595 feet. On the other hand, the upper two requienid units in the Tomasek probably do not have rudist grainstone as their shelfward lateral equivalent, and there the requienid facies itself is primarily very fine grainstone. Caprinid-coral wackestone occurs sporadically in the shelf-margin cores and probably represents a lower energy condition on the shelfal side of the shelf margin.

Shelf-lagoon facies occur in the upper part of the Ruhmann (above 13,643 feet) and in the entire core of the Pace. Up to 30 feet of shelf-lagoon sediments may occur at the top of the Stuart City Formation in the Roessler, Tomasek, and O'Neal wells, but this part of the section was not cored. The Tomasek core begins approximately 40 feet below the top.

Dip section E-E′ (fig. 31).—The facies relationships between two closely spaced wells, the Atlantic Smith and the Shell Roehl, are shown on dip section E-E′. For additional lateral coverage, the Standard of Texas Pace and the Texas Eastern Transmission Garbe have been projected in from greater distances. The Pace is believed to lie on the landward side of the Smith, and the Garbe is located seaward of the Roehl. Core lowest in the section is present only in the lower half of the Smith where upper shelf-slope sediments consist predominantly of coral-stromatoporoid boundstone with some caprinid-coral wackestone.

Shelf-margin facies are present but very thin in both the Smith and Garbe wells. In the Smith, rudist grainstone and coral-caprinid boundstone make up a total of 18 feet of shelf-margin facies; in the Garbe, 93 feet of shelf-margin core comprises the requienid boundstone, coral-caprinid boundstone, and caprinid-coral wackestone facies. The base of these facies is only 60 feet higher in the Garbe than in the more landward-located Smith, and the pattern of upward and seaward migrating facies, so obvious in other dip sections, is much less pronounced in this section. An additional 43 feet of caprinid-coral wackestone occurs higher in the Garbe following an interval of shelf-lagoon facies.

Shelf-lagoon facies occur in all the wells on the section; they include toucasid wackestone, miliolid wackestone, mollusk wackestone, and algae-encrusted caprinid-coral packstone. The most significant feature is the thick section of algae-encrusted caprinid-coral packstone present in the Roehl. This facies occurs also in the Smith, but in thinner units which are broken by beds of miliolid wackestone of similar thickness. Birdseye structures in the miliolid wackestone indicate the presence of many small islands on this part of the shelf. The algae-coated facies extends both directions from the Roehl and Smith to the Garbe and Pace wells but this facies is thinner, the algal crusts are not so well developed, and the fabric is wackestone instead of the packstone of the Roehl and Smith. The distribution and internal variation in fabric of the algae-encrusted facies suggest that it was best developed in the area of the Roehl well, that it became less dominant in both directions, and that it occupied a position just behind the shelf margin or perhaps replaced the shelf-margin facies on a more stable, broad platform.

Vertically within the algae-encrusted facies of the Roehl well there is a change from a fauna more closely allied with that of the shelf margin, at the base, to a fauna more related to the shelf

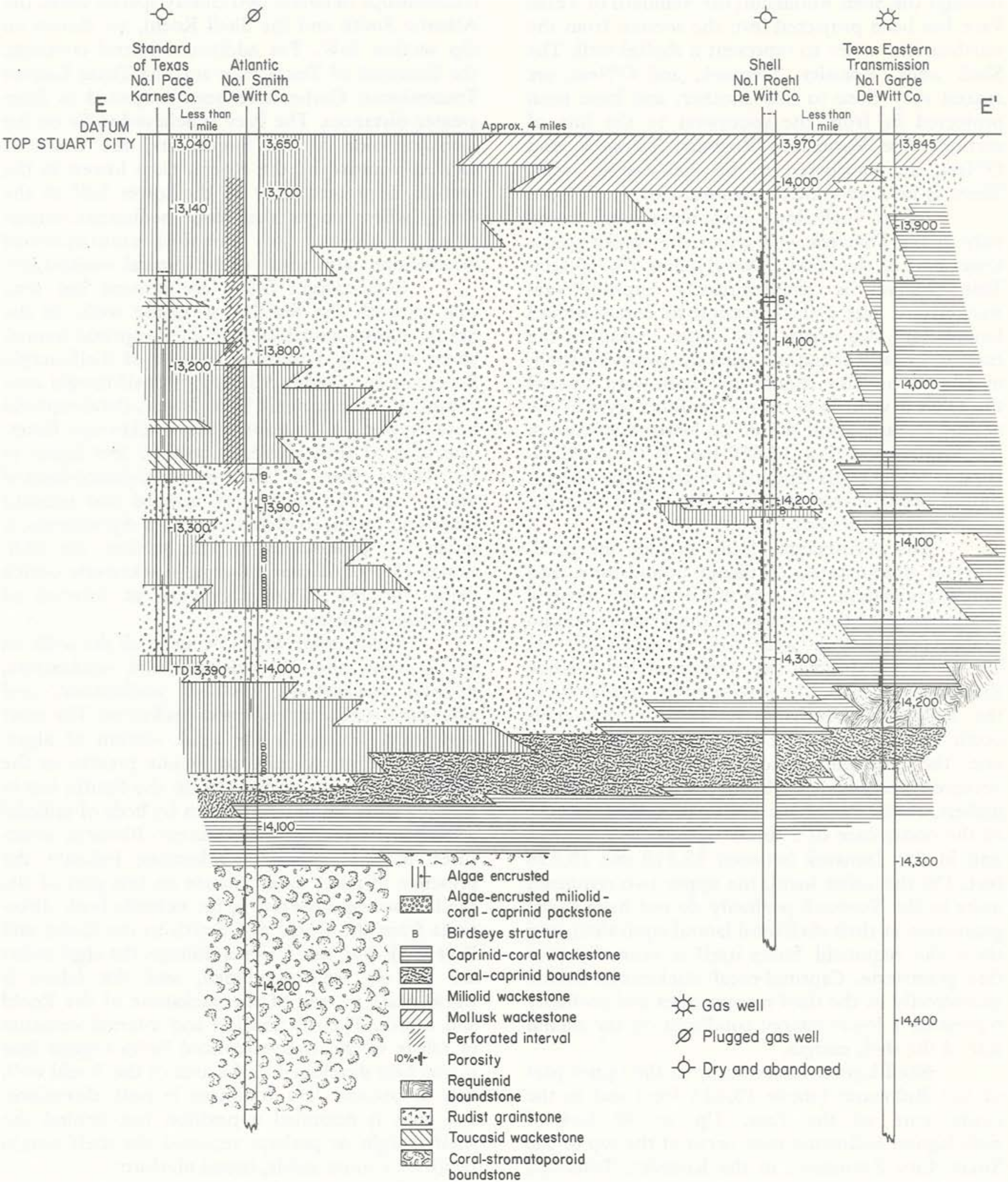


Figure 31. Facies cross section E-E′.

lagoon, toward the top. In the lower part, requienids, corals, and caprinids are common along with a great diversity of other animals such as miliolids, *Dictyoconus*, mollusks, *Solenopora*, and stromatoporoids. The requienids extend upward little more than 100 feet; the corals and caprinids likewise become less abundant upward, and mollusks and miliolids become more significant. This same transition occurs from the Roehl landward toward the Smith and Pace.

DIAGENESIS

Cement from Direct Precipitation

Cement types discussed here are most common in the rudist grainstone facies (fig. 32), but also occur in other grainstone facies and in vugs of other fabrics. Letter designations used for the cement types are after Folk (1965). Vertical distribution of cement types within one grainstone body is shown on figure 19.

Dripstone (precipitated laminated crust) (figs. 33, 34).—Dark-colored, laminar crust which develops either as thickened layers up to 1 mm thick on the bottom side of grains (dripstone) or at grain contacts (meniscus cement). The dripstone may be either very finely and evenly laminated or may contain very irregular, cauliflower-like structure.

Isopachous cement (precipitated fibrous crust) (fig. 35).—Very fine to medium crystalline calcite ($P.F_{2-4}C$). This cement, composed of very fine needles, entirely coats the grains and is in turn coated by impure bladed crust (P.BC).

Radiaxial cement (precipitated bladed crust) (figs. 36-38).—Thick layers of cement composed of crystals up to 1.5 mm long ($P.B_{4-6}C$). The long dimensions of the crystals are perpendicular to the grain surfaces to which they are attached. The boundaries between these calcite blades are very irregular; toward the center of the cavity, they are in contact with equant clear calcite. The equant calcite crystals are commonly in optical continuity with the bladed calcite which they adjoin. Under crossed nicols the bladed calcite has undulose extinction; curved cleavage lines are common. Zankl (1971) interprets the irregular crystal boundaries and the undulose extinction to be the result of recrystallization pressures originating during inversion from aragonite to calcite. This type of cement, termed radiaxial by Bathurst (1959, 1971), is characterized by the medium brown color. This color is the result of abundant fluid inclusions and very finely disseminated organic material, which gives the cement a hazy appearance when examined under high magnification. Many thin sections of the rudist grainstone with radiaxial cement show a very loose packing of the grains (figs. 32, 39a). This loose packing is the result either of intense leaching of matrix prior to deposition of the radiaxial cement or of displacive cementation, in which the grains are forced apart by crystallization of the cement. It is probable that both mechanisms played a role in forming this fabric. Small foraminifers and ostracods occur rarely within the cement.

Precipitated bladed crust occurs also as a thin, clear rim ($P.B_4C$) around grains (isopachous cement, fig. 35). This thin rim commonly lies between the grain and the impure bladed crust described above.

Figure 42b, c shows two examples of precipitated bladed crust occurring within the void left after the leaching of a rudist shell. At the bottom of the void is a geopetal fill of ostracods; on this fill and around the remainder of the shell is the thick layer of bladed cement.

Precipitated equant calcite (figs. 22, 23, 34, 35, 36c, d, 38).—Equidimensional medium to coarse crystalline calcite ($P.E_{4-5}$). This cement is clear and colorless, and has straight contacts with neighboring crystals. Equant calcite fills the remaining openings between and within grains and in fractures which cut all other types of cement.

Neomorphic Calcite

Neomorphic equant calcite (fig. 39).—Medium to coarse crystalline clear calcite ($N.E_{4-6}$) which takes the place of the original material of most shells. In some shell fragments, vestiges of the original structure are preserved (fig. 39b); in most, all original structure is lost and only equant calcite and the micrite rim preserve the original outline of the shell (fig. 39c).

Impure neomorphic calcite (figs. 34a, 40).—This impure medium to coarse crystalline calcite ($N.B_{4-5}$) is similar in appearance to the precipitated bladed crust described earlier. However, the type included here occurs within the micrite envelope of the grain and is apparently neomorphic after the neomorphic or precipitated equant calcite. In figure 39b, the original shell structure still preserved in the equant calcite toward the center of the grain is also preserved in the bladed calcite along the edges. In figure 34a, one skeletal grain shows a front of impure neomorphic calcite after clear neomorphic equant calcite. Orme (1970) and Orme and Brown (1963) have recognized this type of calcite from the Carboniferous of northern England and Wales and have interpreted it as originating through recrystallization of calcite mudstone.

Timing of Diagenesis

Porosity in the grainstone bodies was 30 to 40 percent at the time of deposition and perhaps higher in grainstones with large, irregular rudist fragments. Today, porosity within these same grainstone bodies is lacking or is very low in a few thin intervals. This loss of up to 40 percent porosity is the result of massive cementation. The several cement types previously discussed fill this primary porosity in an easily recognizable, orderly sequence (fig. 41). However, a knowledge of the sequence of cementation does not necessarily tell us the timing of cementation. Therefore, to get at the timing we must first identify those cements that we can recognize with confidence as having been deposited in a particular setting.

Micrite rims are widely distributed and are present on most grains. These rims formed either as an algal coating or from alteration of the edges of the grains by boring organisms (Bathurst, 1966; Purdy, 1968). In either case, the rims formed on grains which were loose on the sea floor and, therefore, at the time of deposition.

Isopachous cement forms a thin layer over the micrite rim, and is irregular in its distribution and not so widespread as the micrite rims and radiaxial cement. In appearance and distribution, it compares favorably with beachrock and submarine cement forming today in many shallow marine areas. Another evidence of the early, submarine origin of isopachous cement is its occasional alternation with micrite rims. Likewise, it occurs in alternating layers with geopetal cavity fill (fig. 42a), obviously of submarine origin because of the presence of marine organisms in the internal sediment.

Dripstone and meniscus cements occur either directly on the micrite rim (most common) or on the layer of isopachous cement. These asymmetrical cements are indicative of areas of periodic wetting and drying where water is left behind at grain contacts (meniscus) and as droplets on the bottoms of grains. On further drying, carbonate is precipitated there from the saturated water droplets. These conditions are best fulfilled in the vadose environment (Dunham, 1971) but can also occur in the marine intertidal environment. Taylor and Illing (1969) describe dripstone development on intertidal beachrock from the Qatar Peninsula, Persian Gulf; Purser (1969) illustrated well developed dripstone from the Middle Jurassic of the Paris basin, France, and attributed it to an intertidal beachrock environment. Consequently, the dripstone and meniscus cements in the Stuart City Limestone are believed to have been deposited in a vadose or intertidal environment. The dripstone and meniscus cements are, in turn, overlain by radiaxial cement (most common) or equant calcite.

Radiaxial cement forms a thick layer of calcite over any of the previously described cement types—micrite rims, isopachous cement, and dripstone. Where mollusk shells have been leached, the void space thus formed is filled with radiaxial cement, clearly dating this cement as later than the shell-leaching event. Pingitore (1970) found in the Pleistocene of Barbados that skeletons of the coral *Acropora palmata* underwent dissolution in the subaerial stage; cementation within the voids formed by this dissolution took place later when the remaining aragonite inverted to calcite. Thus the mollusk shells discussed above were probably leached in the subaerial or vadose environment. Abundant ostracods occur at the bottom of some vugs formed from this leaching (fig. 42b, c); subsequent induration by radiaxial cement resulted in their incorporation. No other sediment has been found deposited within or later than the radiaxial cement. It therefore was probably deposited by phreatic-meteoric water in the shallow subsurface. The water was rich in organic matter, as evidenced by the abundance of organic "sludge" within the radiaxial cement, giving it the brown color. Bathurst (1971) described radiaxial cement in detail. Similar-appearing cement has been illustrated by many authors but interpretations of its origin vary considerably. A few of the authors who have made significant interpretations are Dunham, subaerial (1969, 1972); Fischer, subaerial or subaqueous (1964); Friedman and Kolesar, subaerial from fresh water (1971); Kendall, percolating ground water just beneath the surface (1969); Orme, recrystallization and as tufa (1970); Orme and Brown, late diagenetic (1963); Purser, intertidal (1969); Schmidt, early diagenetic submarine (1971); and Zankl, synsedimentary (1971).

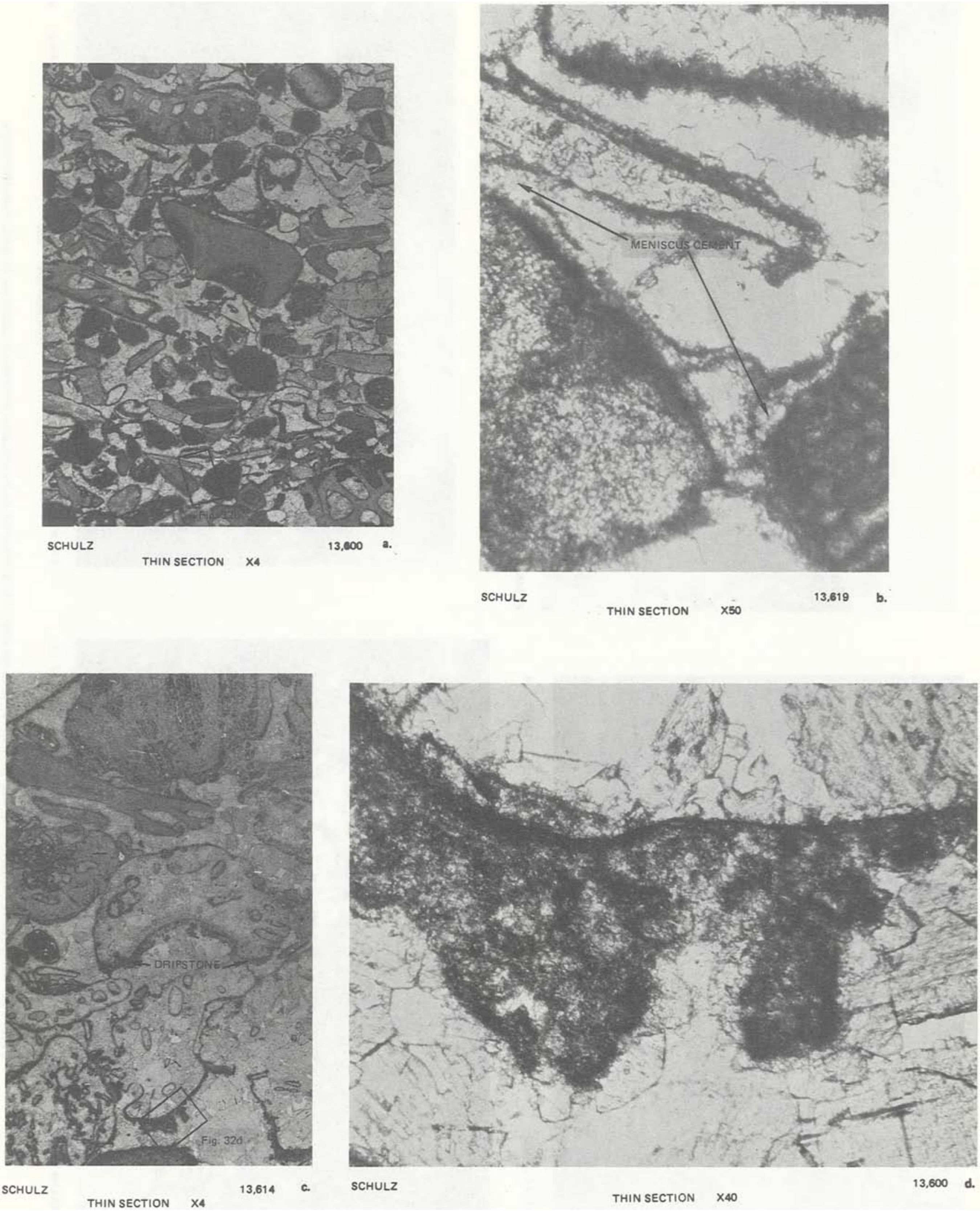


Figure 32. Meniscus and dripstone cement. a, b. Meniscus cement. A second micrite rim is developed on the meniscus cement. c, d. Dripstone cement.

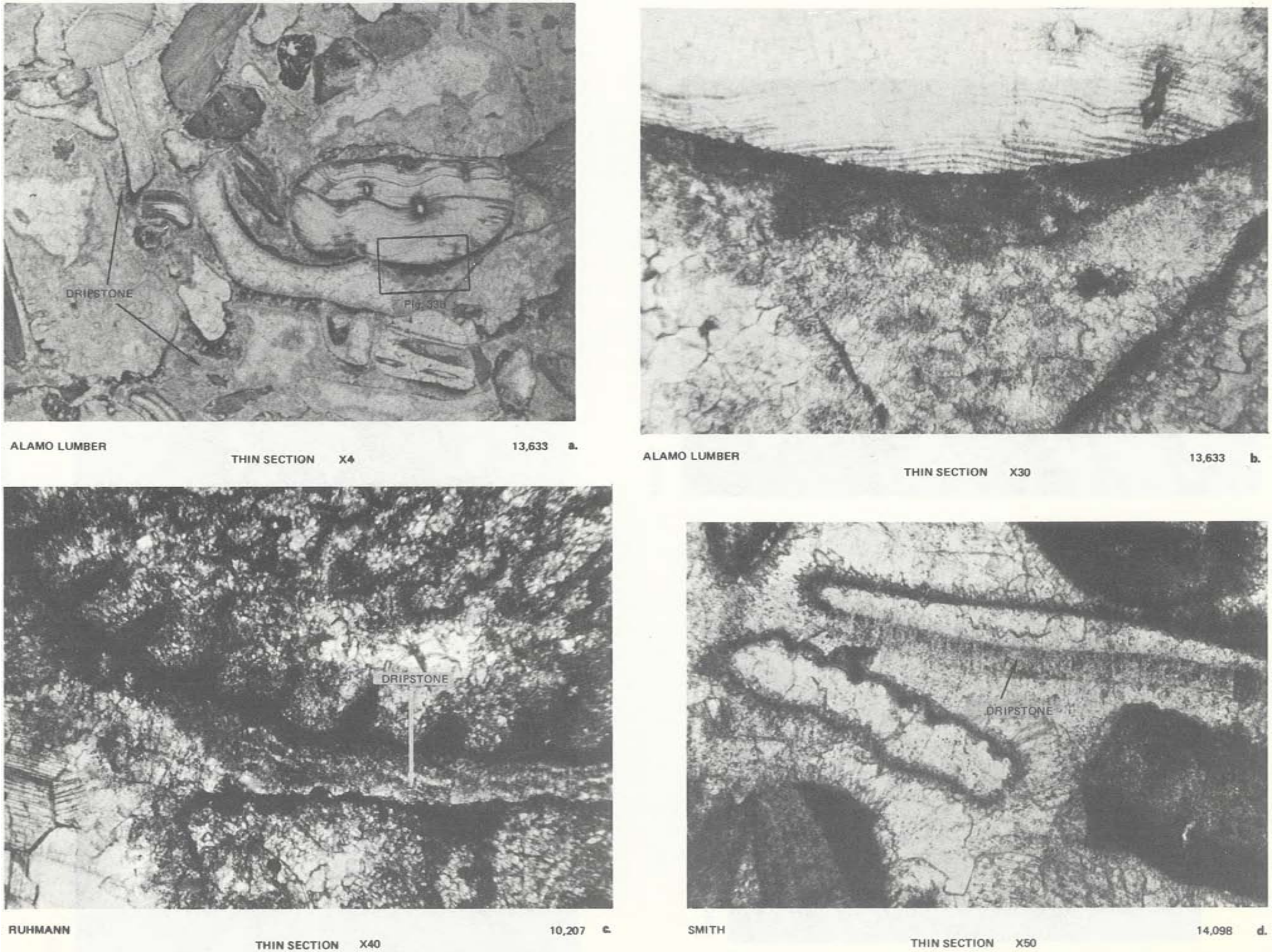


Figure 33. Dripstone cement. a-d. The dripstone is commonly dark colored and contains irregular laminae. In addition, the large grain in the upper right corner of (a) has a replacement front with impure neomorphic calcite in the lower half replacing equant calcite in the upper half.

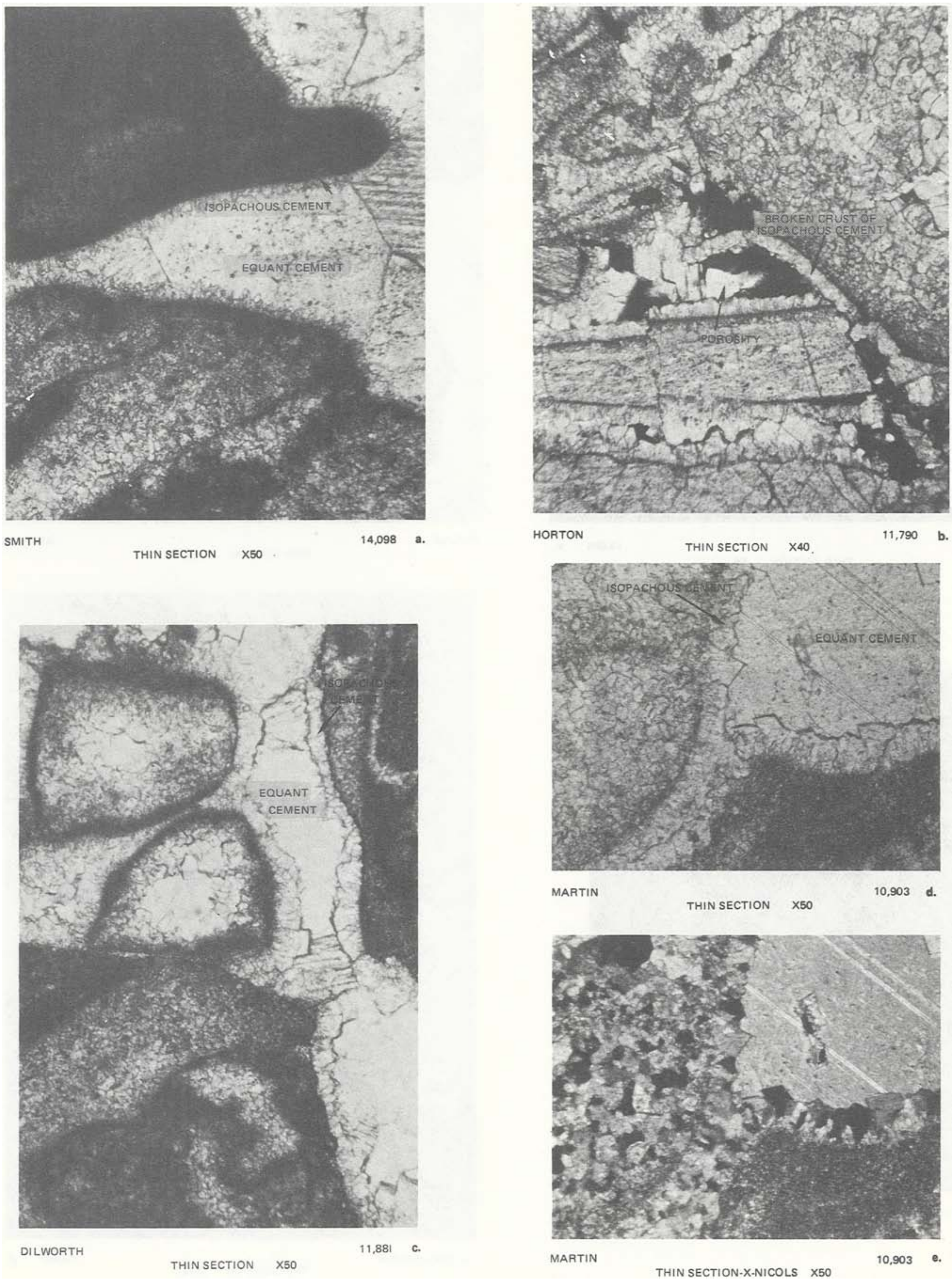


Figure 34. Isopachous cement. a-c. Grainstones in which intergranular spaces were lined with distinct, even layers of isopachous cement; the remaining space was then filled with coarse equant calcite. In (b) the isopachous layer was broken from compaction before the precipitation of the equant cement.

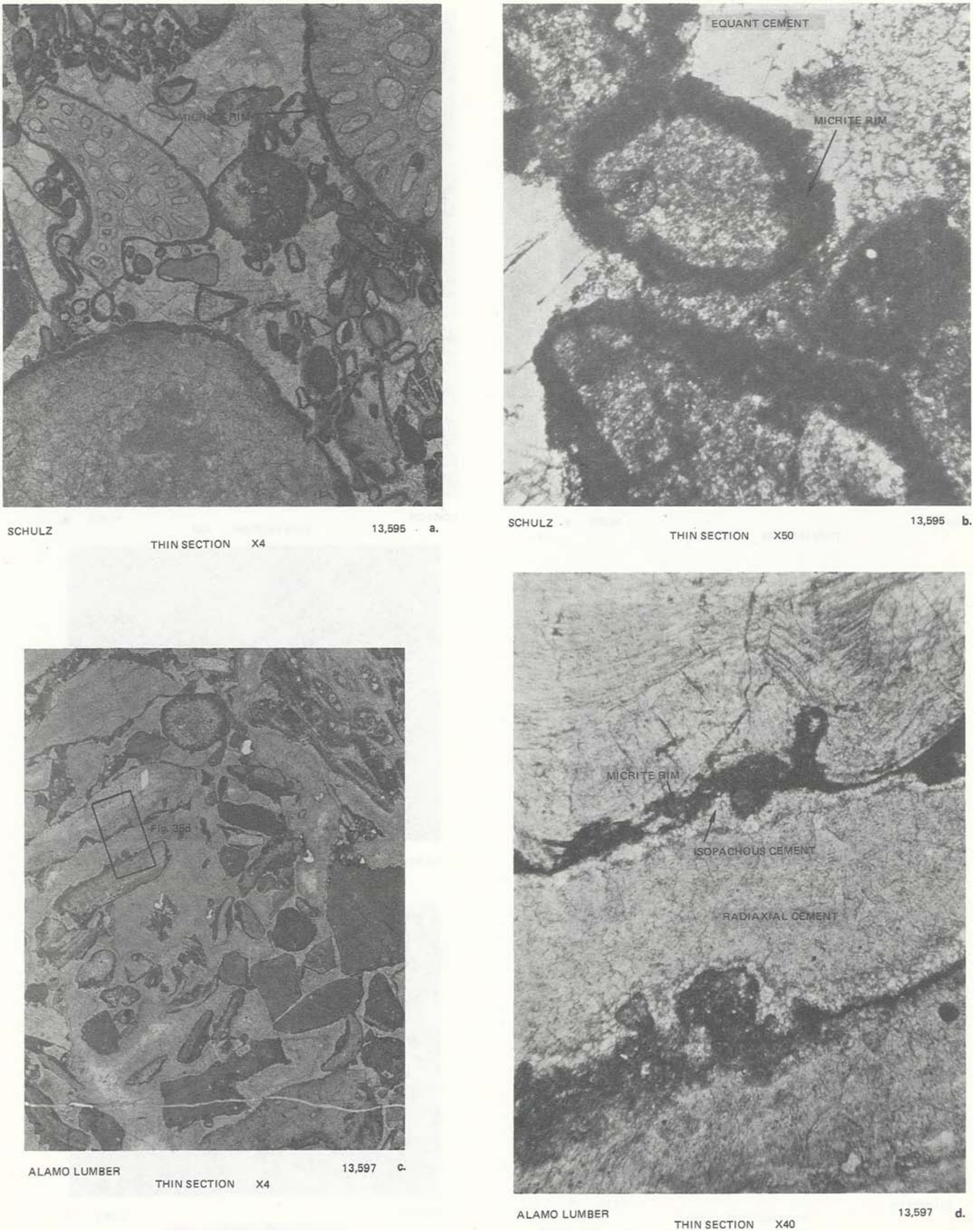
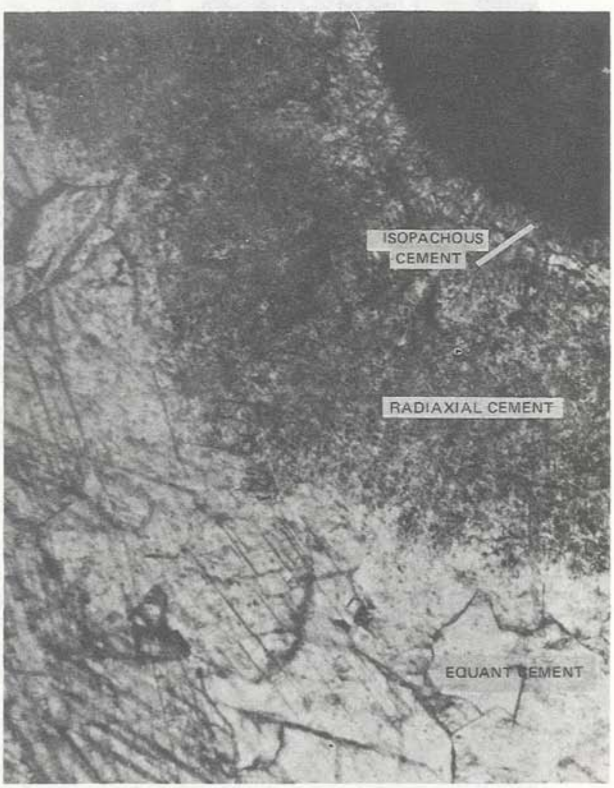


Figure 35. Micrite rims. a, b. Loosely packed rudist grainstone with only equant calcite cement. Micrite rims are well developed. c, d. Loose packing in grainstone probably developed either from leaching of matrix or from displacive precipitation of calcite. Micrite rims, isopachous cement, and radiaxial cement are developed.

ALAMO LUMBER 13,647 a.
THIN SECTION X4

ALAMO LUMBER 13,638 b.
THIN SECTION X4



ALAMO LUMBER 13,647 c.
THIN SECTION X50

ALAMO LUMBER 13,647 d.
THIN SECTION-X-NICOLS X50

Figure 36. Radiaxial cement. a, b. Thick radiaxial cement developed over a thin isopachous layer. Enlargements of the cement in (a) are shown on (c) and (d). Enlarged views of (b) are shown on figure 37 (c) and (d). c, d. Layer of radiaxial cement almost 1 mm thick which contains the characteristic high percentage of dark impurities. The contact between the impure radiaxial cement and the clear equant calcite is sharp, but under crossed nicols (b) some equant crystals are clearly syntaxial overgrowths on the radiaxial crystals.

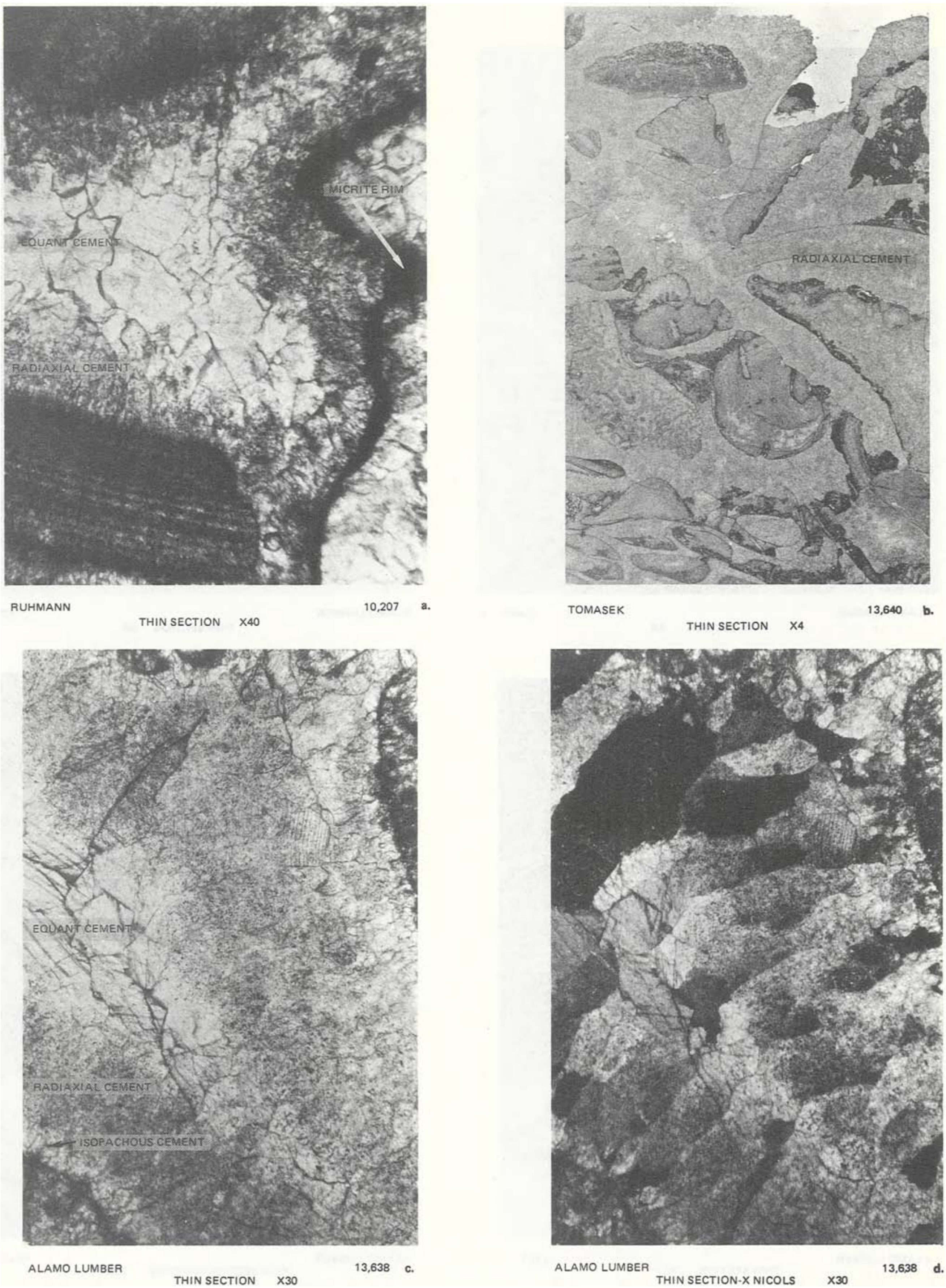
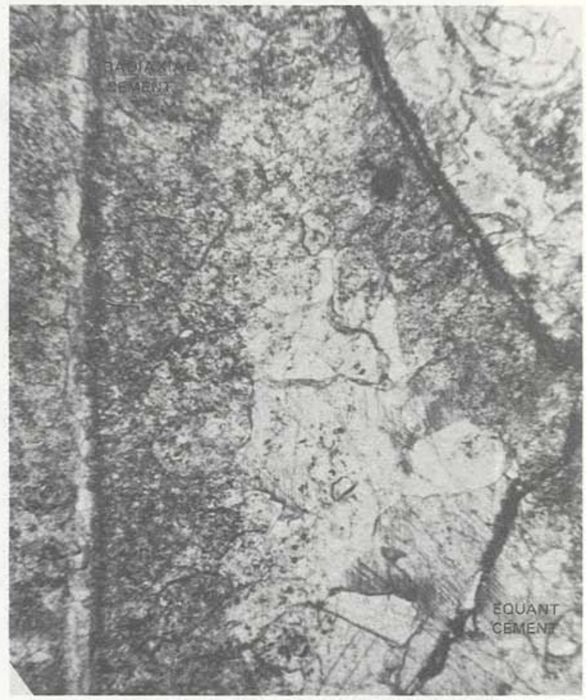


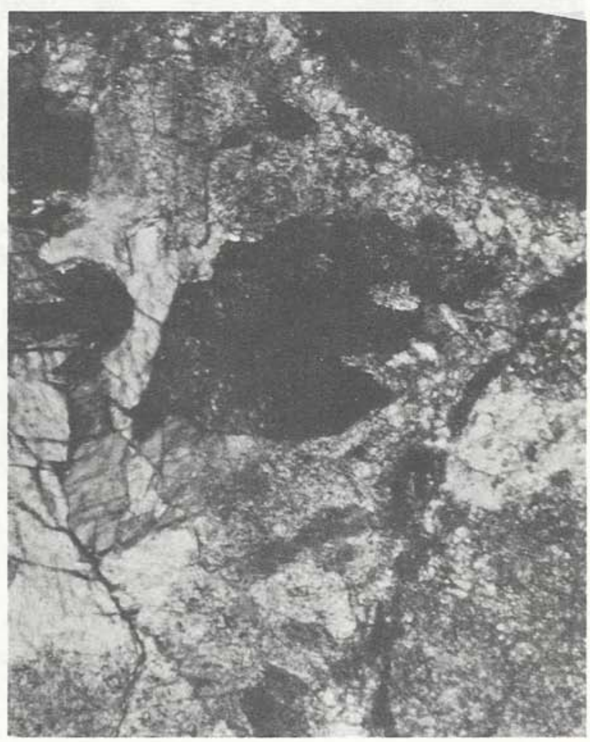
Figure 37. Radiaxial cement. a. Radiaxial cement immediately over micrite rim. Equant calcite fills the remaining void space. Note the abundant dark-colored impurities in the echinoid fragment on the lower left. b. Massive cementation by radiaxial cement. The only other cement type present is a small amount of equant, which fills the small voids left in the larger intergranular spaces. c, d. Large blades of radiaxial cement extending into a void from the grain surfaces. Much of the equant cement in the center is in optical continuity with the radiaxial crystals.

MARTIN 10,360 a.
THIN SECTION X4



MARTIN 10,360 b.
THIN SECTION X40

ALAMO LUMBER 13,635 c.
THIN SECTION X50



ALAMO LUMBER 13,635 d.
THIN SECTION-X NICOLS X50

Figure 38. Radiaxial cement. a, b. Massive cementation between grains by radiaxial cement. Clear equant calcite fills the centers of the larger spaces. Impure neomorphic calcite in the large skeletal fragment in the top center of (a) is after neomorphic equant calcite. c, d. Radiaxial and equant cement in plain- and cross-polarized light, respectively, showing the syntaxial growth of equant calcite on radiaxial.

Figure 39. Neomorphic equant calcite. a. Grainstone with neomorphosed shells. Parts of the gastropod on the lower right have been neomorphosed to equant calcite (b) but much may have been leached and the void filled with radiaxial cement. The loose packing may be the result of displacive precipitation. b. Neomorphic equant calcite with original shell structure preserved. c. Mollusk shell fragments neomorphosed to equant calcite.

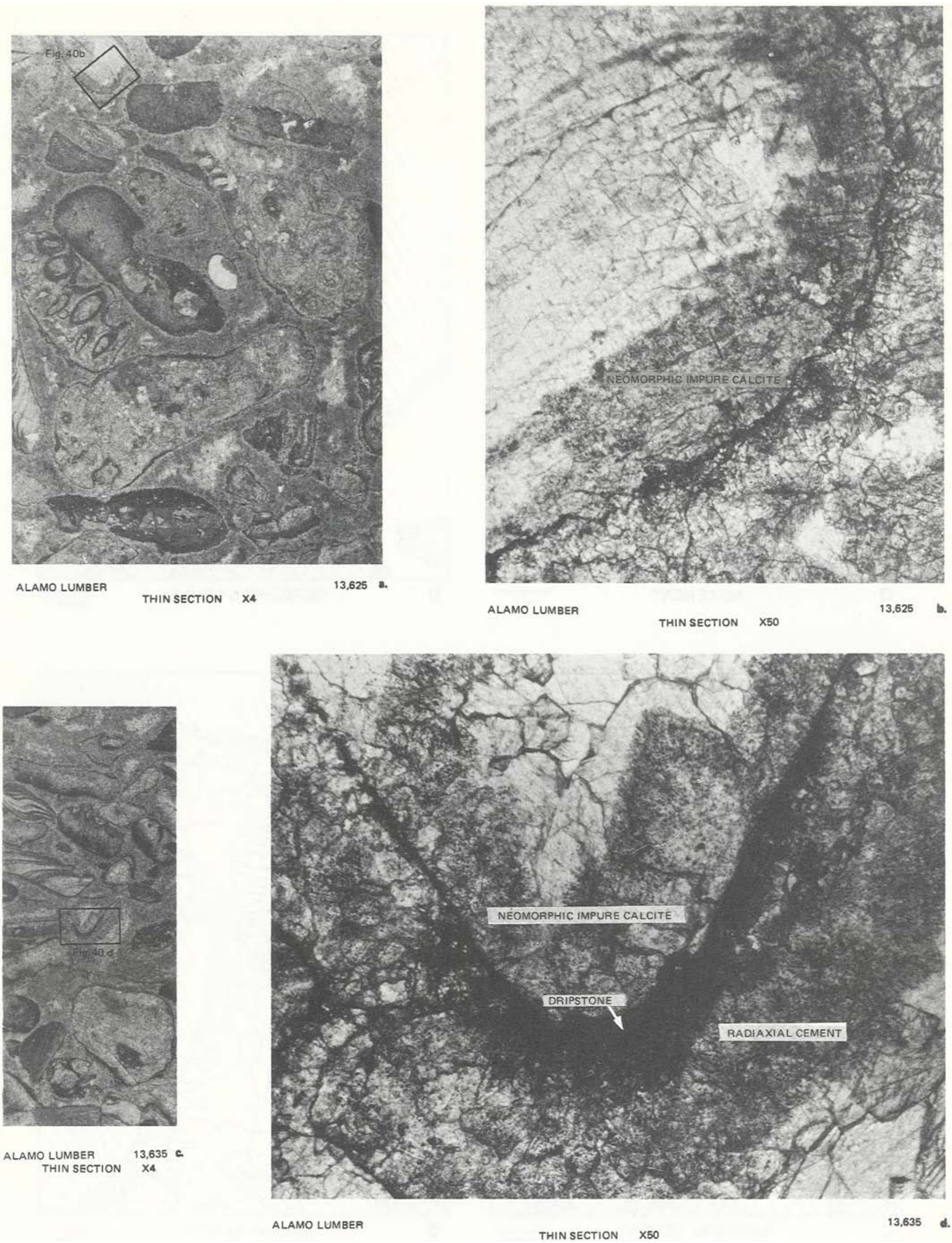


Figure 40. Neomorphic impure calcite. a, c. Grainstone with a thin rim of isopachous cement, very thick impure radiaxial cement, and small patches of clear equant calcite. The edges of the neomorphosed shell fragments are altered to impure calcite. b, d. Enlargement of the edge of a grain from (a) showing the rim of the grain. Dripstone is developed on the bottom of the grain illustrated in (d).

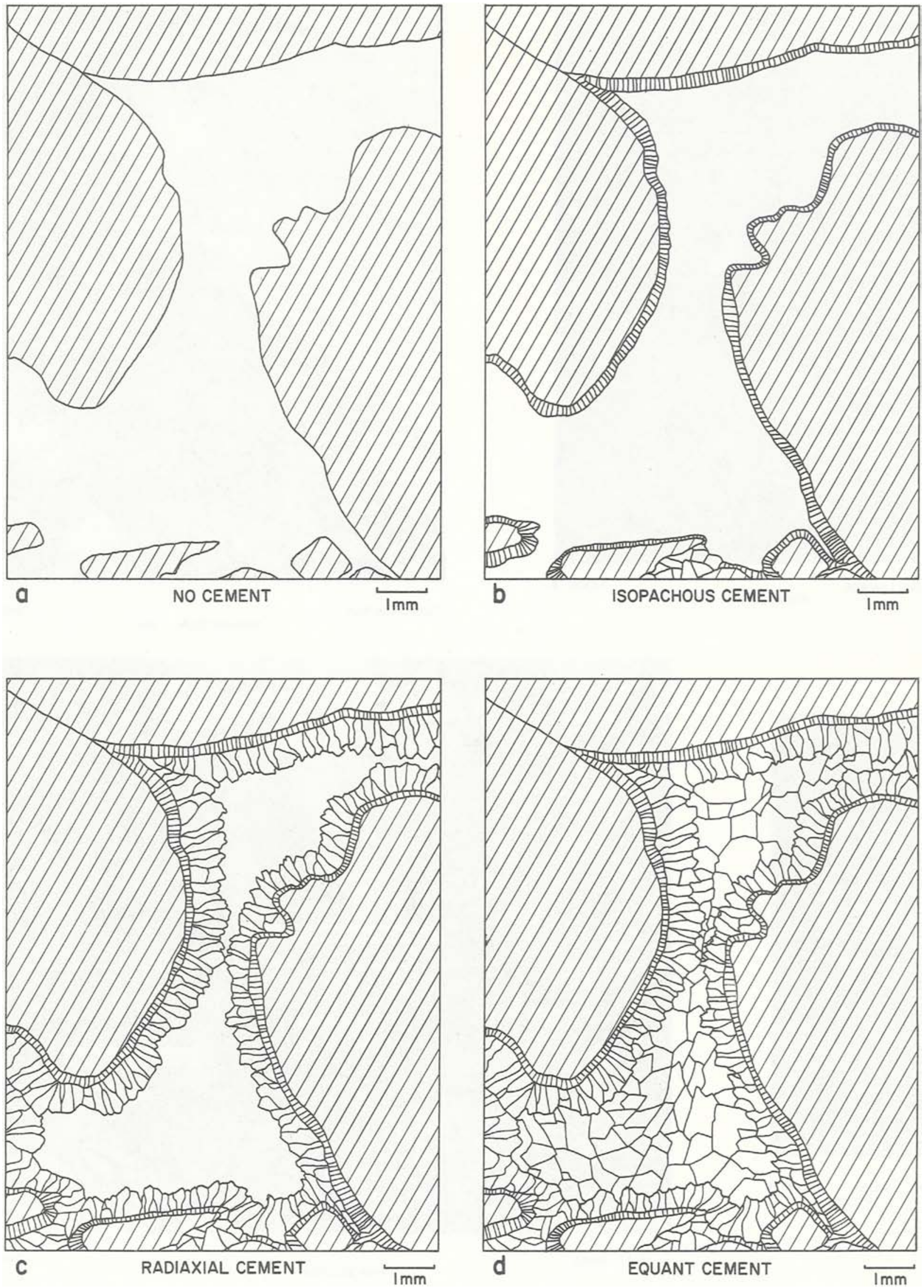


Figure 41. Sequence of cement types in the rudist grainstone. a. Grains with no cement. b. Isopachous cement. c. Radiaxial cement. d. Equant cement.

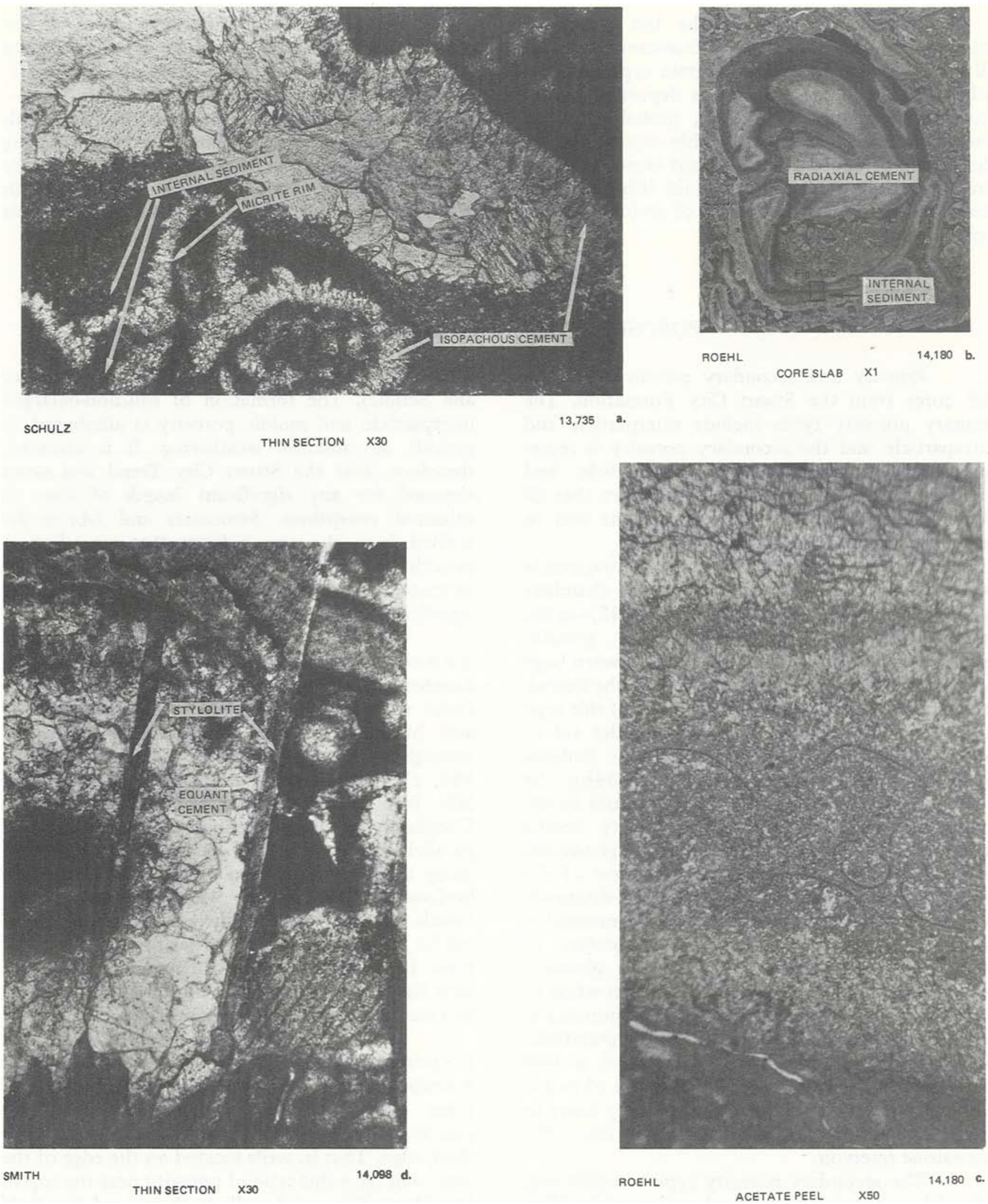


Figure 42. Timing of diagenesis. a. Isopachous cement around the edges of a void covered by a layer of marine sediment with a micrite rim and a second layer of sediment. The isopachous rim is interpreted as submarine in origin. b. Radiaxial cement filling a void which resulted from the leaching of a requienid shell. The leaching is interpreted as having taken place either in the surf zone or in subaerial vadose conditions. Thus the cement is interpreted as phreatic-meteoric in origin. The vadose silt layer at the bottom of the void is enlarged in (c). c. Vadose silt with thin-shelled ostracods, enlarged from (b). d. Equant cement truncated by stylolites.

Equant cement fills the last remaining intergranular spaces. It also fills fractures which cut all other cement types and all grain types. On the other hand, equant cement was deposited before stylolites developed (fig. 42d), probably in the deep subsurface. Thus, we are able only to bracket the timing of deposition of equant cement as after the formation of fractures within lithified limestone and before the formation of stylolites in the deep subsurface.

An electron-probe traverse across all the cement types disclosed that there is a significantly lower proportion of magnesium in the clear, equant calcite as compared to the other types—micrite rim, dripstone, isopachous, and radiaxial. Folk (1973) believes that coarse, equant cements low in magnesium were crystallized from deeply buried connate waters which were low in magnesium because of its removal by clay minerals or by the growth of dolomite.

POROSITY TYPES AND DISTRIBUTION

Primary and secondary porosity occur in the cores from the Stuart City Formation. The primary porosity types include interparticle and intraparticle and the secondary porosity is represented by solution-enlarged interparticle and moldic types (table 3). For the most part, they all occur in amounts less than 5 percent and in relatively thin intervals (figs. 27-31).

Of the primary porosity types, intraparticle porosity—that which remains within the chambers of organisms (figs. 18a, 22b, 23a, 24a, 43)—is the most widespread. A similar type, growth-framework porosity, occurs as space between large organisms which are bound together in the boundstone facies (fig. 24a). However, rocks of this type have very low permeability without the aid of other porosity types to connect these isolated openings. Interparticle porosity (fig. 34b), the other primary type, occurs between grains in the grainstone facies; interparticle porosity results from incomplete cementation of a grainstone body. In the Stuart City, however, most of the primary interparticle porosity has been destroyed by several stages of cementation. This cementation took place at three times: synsedimentary or submarine; early, shallow subsurface phreatic-meteoric; and late, deep subsurface. Preservation of large amounts of primary interparticle porosity is aided by keeping fresh water out of the grainstone body either by subsidence or lack of a well developed fresh-water lense. Preservation of such a carbonate reservoir has been attributed by many to early migration of hydrocarbons into the grainstone reservoir.

The secondary porosity types—moldic (fig. 44a, b) and solution-enlarged interparticle (figs. 10b, 44c)—occur most commonly in the grainstone and boundstone facies; moldic porosity occurs in only one wackestone facies—the miliolid wackestone—and only in two wells (Alamo Lumber and Schulz). The formation of solution-enlarged interparticle and moldic porosity is attributed to periods of subaerial weathering. It is assumed, therefore, that the Stuart City Trend was never exposed for any significant length of time to subaerial conditions. Structures and fabrics described from the core indicate that several short periods of vadose weathering occurred, but not extensively enough to result in the formation of significant reservoirs.

Vertical fractures are scattered throughout the cored intervals (figs. 10b, 44d, e). In the Alamo Lumber well they occur in the mollusk wackestone facies where they are partially filled with calcite and bitumen. Vertical fractures are abundant throughout the core from the Kahanek well (fig. 44d, e); they are most abundant from the lower 300 feet in the requienid boundstone facies. Commonly, a large number of these fractures parallel one another and extend for several feet along the long dimension of the core. Abundant horizontal fractures (fig. 44f) occur in thin intervals of the HOR 2 Dilworth. No evidence of calcite lining or oil stain has been found related to these fractures. Therefore, it is possible that these core fractures were induced during or after drilling and were not present in the subsurface.

Because the secondary porosity types and the primary interparticle porosity occur only in the boundstone and grainstone facies, the location of these porosity types is dependent upon the position of the particular well with respect to the shelf edge. That is, wells located on the edge of the shelf will have this type of porosity near the top of the Stuart City, and wells back toward the shelf lagoon will have the same type of porosity progressively lower in the section (figs. 27-31). Porosity within body chambers of organisms, intraparticle,

Table 3. Distribution of porosity types in the facies of the Stuart City Trend.

		FACIES							
		Miliolid wacke-stone	**Mollusk-miliolid grainstone**	**Rudist grainstone**	**Requienid boundstone**	**Algae-encrusted miliolid-coral-caprinid packstone**	**Caprinid-coral wackestone**	**Coral-caprinid boundstone**	**Coral-stromato-poroid boundstone**
POROSITY TYPES	solution-enlarged inter-particle					Roehl lined vugs <5%		HOR 1 Dilworth <5%	Tomasek <10% Horton Roessler <5%
	moldic	Alamo Lbr. Schulz <5%	Alamo Lbr. Kahanek up to 10%	Kahanek HOR 2 Dilworth up to 15%					
	inter-particle		Alamo Lbr. HOR 1 Dilworth up to 10%	Kahanek HOR 2 Dilworth HOR 1 Dilworth up to 10%					Scattered throughout in geopetal-filled cavities <5%
	intra-particle	Alamo Lbr. Schulz <5%	Alamo Lbr. Martin Schulz <5%	Alamo Lbr. Martin Schulz <5%	Alamo Lbr. Peschel Schulz Smith Tomasek <5%		HOR 1 Dilworth SOT 1 Dilworth Garbe Horton Martin Schulz Smith <5%	Schulz <3%	

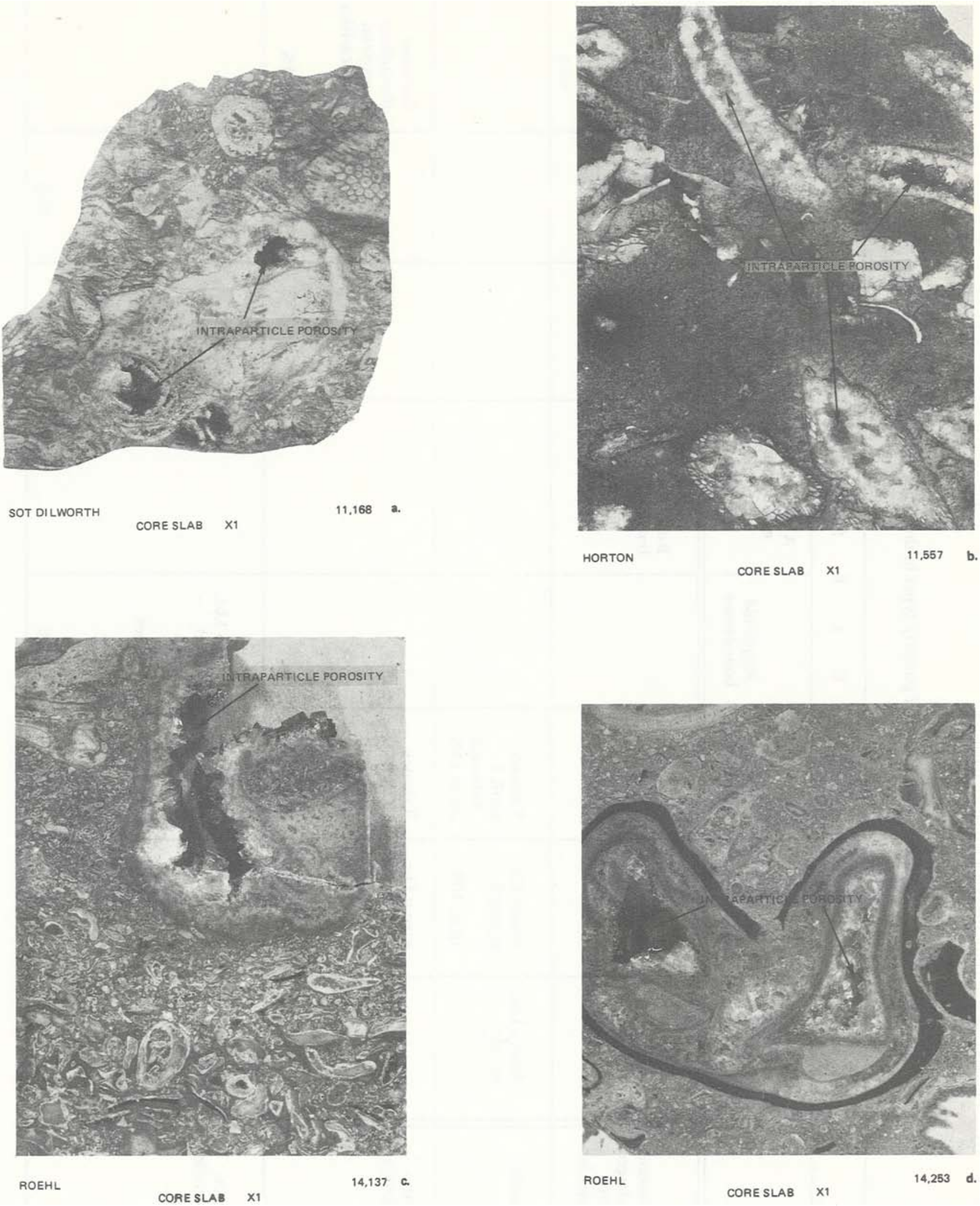


Figure 43. Primary intraparticle porosity. a. Intraparticle porosity preserved within the body chambers of caprinids. b, c. Solution-enlarged, cementation-reduced intraparticle porosity within the body chambers of caprinids. d. Internal sediment- and cementation-reduced intraparticle porosity within the body chamber of a requienid.

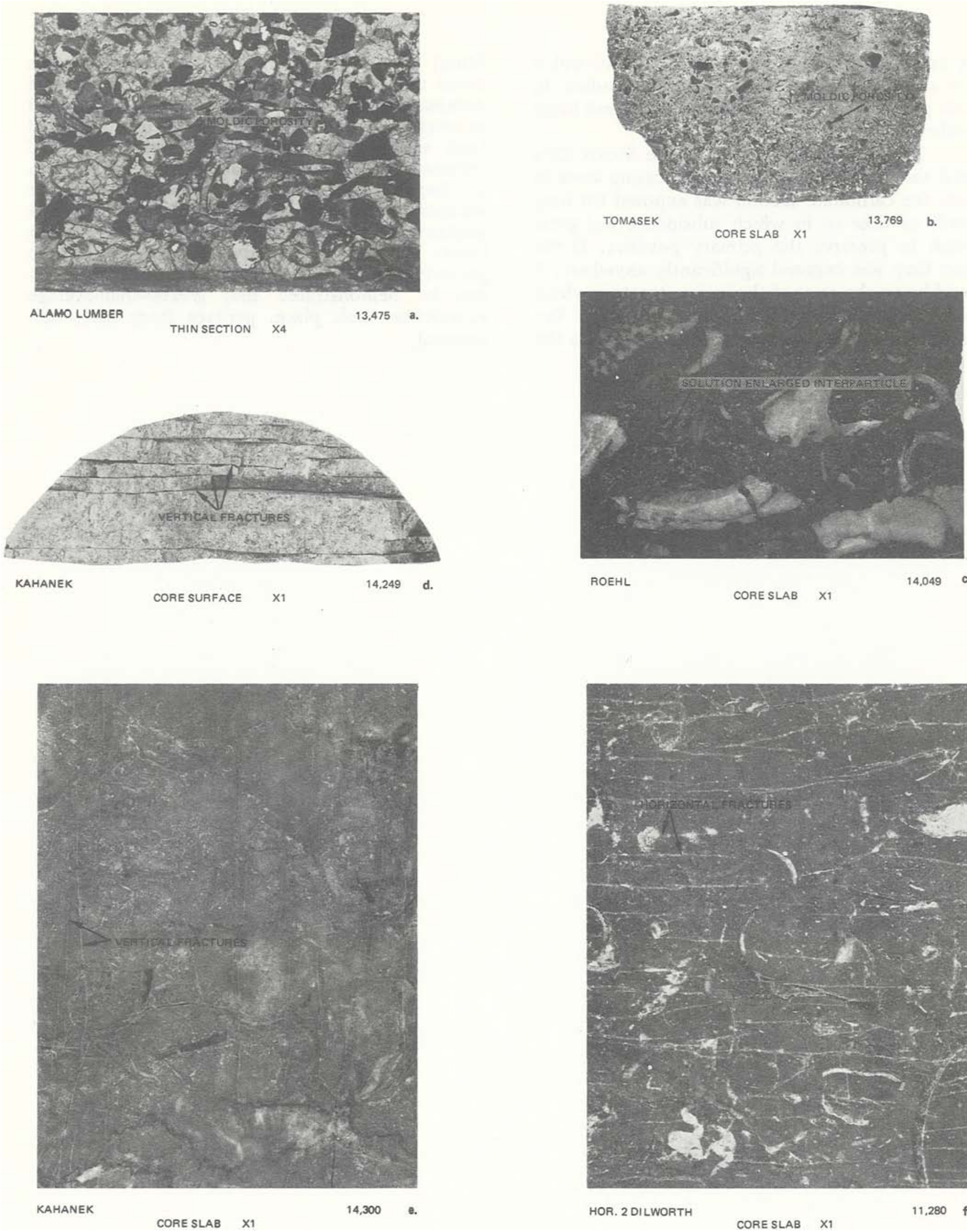


Figure 44. Secondary porosity. a. Moldic porosity in a mollusk-miliolid grainstone. The white areas are porosity. b. Moldic porosity in a locally high-grain portion of the caprinid-coral wackestone facies. The black areas are porosity. c. Solution-enlarged interparticle porosity in the algae-encrusted miliolid-coral-caprinid packstone facies. The light-colored areas are large skeletal fragments. The dark-colored area consists of highly altered matrix and fine grains which are cemented together by heavy hydrocarbon. This interval is 10 feet thick. d, e. Vertical fractures commonly spaced 1 centimeter to only a few millimeters apart. f. Horizontal fractures.

may occur anywhere vertically in the section but is most common in facies with caprinid rudists in which porosity is present within the caprinid body chambers.

Further exploration along the Stuart City Trend should, then, be aimed at locating areas in which the carbonate section was exposed for long periods of time or in which subsidence was great enough to preserve the primary porosity. If the Stuart City was exposed significantly anywhere, it should be on the crest of the major structure which trends perpendicular to the shelf edge—the San Marcos Arch. The San Marcos Arch intersects the Stuart City Trend in DeWitt County; two wells cored the carbonate section here and encountered dominantly algae-encrusted packstone, interpreted as originating in very shallow water but protected from wind-induced wave action and strong tidal currents. This protection may have resulted from the location of the shelf margin a short distance seaward of these facies and, if exposed to subaerial weathering, the carbonates here would contain higher secondary porosity. Primary grainstone porosity, on the other hand, will occur where it can be demonstrated that greater-than-average subsidence took place, perhaps from early salt removal.

MATERIALS AND PROCEDURES

This report is based almost entirely on the detailed study of 10,304 feet of core from 20 wells located along the Stuart City Trend. These wells are distributed along this trend from Waller County on the north to La Salle County on the south. Following is a list of the wells:

Well	Core Coverage	Total feet of core
Waller County		
Shell No. 1 Chapman	17,189-17,258	2,546
	17,288-17,615	
	17,687-18,065	
	18,070-18,080	
	18,122-18,975	
	18,980-19,889	
Austin County		
Mitchell No. 1 Peschel	16,266-16,299	257
	16,341-16,552	
	16,602-16,615	
Lavaca County		
Socony Mobil No. 1 Kahanek	13,552-14,350	798
DeWitt County		
Atlantic No. 1 Smith	13,878-14,067	392
	14,073-14,276	
Shell No. 1 Roehl	13,957-14,127	346
	14,137-14,289	
	14,299-14,323	
Texas Eastern Transmission No. 1 Garbe	14,043-14,241	198
Karnes County		
Standard of Texas No. 1 Pace	13,140-13,390	250
Bee County		
Shell No. 1 Ruhmann	13,453-13,492	244
	13,505-13,526	
	13,552-13,605	
	13,623-13,705	
	13,711-13,733	
	13,738-13,765	
Shell No. 1 Roessler	14,044-14,086	42
Shell No. 1 Tomasek	13,424-15,387	1,963
Shell No. 1 O'Neal	13,635-13,734	99
Live Oak County		
Tenneco No. 1 Alamo Lumber	13,340-13,375	269
	13,380-13,449	
	13,454-13,526	
	13,593-13,642	
	13,647-13,691	
Tenneco No. 1 Schulz	13,417-13,848	556
	13,862-13,987	
Standard of Texas No. 1 Isaacks	12,435-12,453	174
	12,496-12,501	
	12,513-12,516	
	12,543-12,547	
	12,562-12,571	
	12,598-12,605	
	12,613-12,622	
	12,639-12,708	
	12,713-12,763	
McMullen County		
Amerada No. 1 Horton	11,538-11,621	237
	11,657-11,679	
	11,687-11,720	
	11,727-11,826	
Standard of Texas No. 1 Dilworth	11,002-11,043	138
	11,155-11,252	
Humble No. 1 Dilworth	11,100-11,280	807
	11,288-11,915	
Humble No. 2 Dilworth	10,210-10,247	
	10,669-?	
LaSalle County		
Standard of Texas No. 1 South Texas Syndicate	10,520-10,531	11
Stanolind No. 1 Martin	10,207-10,314	777
	10,345-11,015	

All the cores were sawed lengthwise and one sawed surface was etched with dilute hydrochloric acid. The etched surface was examined under low magnification with a binocular microscope, and the following features were recorded on a graphic logging form with a scale of 1 inch = 10 feet: mineral composition, pore type, porosity, nature of contacts, structures, texture, fabric, grain size, crystal size, crystal shape, color, fossils, and cement. A total of 186 thin sections were prepared from 11 wells where more detail was deemed necessary, such as the identification of diagenetic fabrics. Using the detailed information obtained above, the rocks studied were grouped into general facies types and these were used on the cross sections included in this report.

The detailed graphic logs of cores used in the study are not included in this report. However, those interested in more detail may obtain copies of these logs from the Bureau of Economic Geology open files for the cost of reproduction.

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